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LAKE SUPERIOR REGION

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LAKE SUPERIOR REGION

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Prepared under the direction of W. O. Hotchkiss

INTRODUCTION

By C. K. Leith

THE ORE DEPOSITS

Around Lake Superior, in the States of Michigan, Wisconsin, and Minnesota and the Province of Ontario, is an area of highly mineralized pre-Cambrian rocks representing part of the south margin of the great pre-Cambrian shield of North America. It produces about 85 per cent of the iron ore of the United States and 10 per cent of its copper. Production is confined to the portion within the United States. The region has produced more than 1,500,000,000 tons of iron ore and 4,000,000 tons of metallic copper. Reserves of iron ore now known promise a further life of about 20 years at the present rate of production, after which there will be a falling off due to the beginning of exhaustion of the Mesabi range of Minnesota, which has been the principal producer. Production of copper is already waning because of low grade, great depth, and high cost.

Copper mining has been continuous since 1844 in the Keweenaw district of Michigan. Iron mining began in the Marquette district of Michigan in 1848 and slowly spread over other parts of the region. The Menominee district was opened in 1872, the Crystal Falls, Florence, and Iron River districts in 1880, the Gogebic district in 1884, the Vermilion district in 1885, the Mesabi district in 1891, and the Cuyuna and Baraboo districts in 1903.

GEOLOGIC SUCCESSION

The Lake Superior region (see fig. 1) has been of special interest to students of pre-Cambrian geology because it presents the longest and most varied pre-Cambrian succession that has been definitely worked out. Its content of valuable iron and copper ores has made possible more intensive and detailed studies than have been accorded to extensive pre-Cambrian areas elsewhere. For over half a century the region has been under continuous investigation by State and Federal surveys of the United States, by Provincial and Dominion surveys of Canada, and by geologic staffs attached to the mining companies.

This has resulted in many notable geologic publications, of which the monographs on the several districts and on the region as a whole (Monograph 52) and the professional paper on the copper deposits of Michigan, all published by the United States

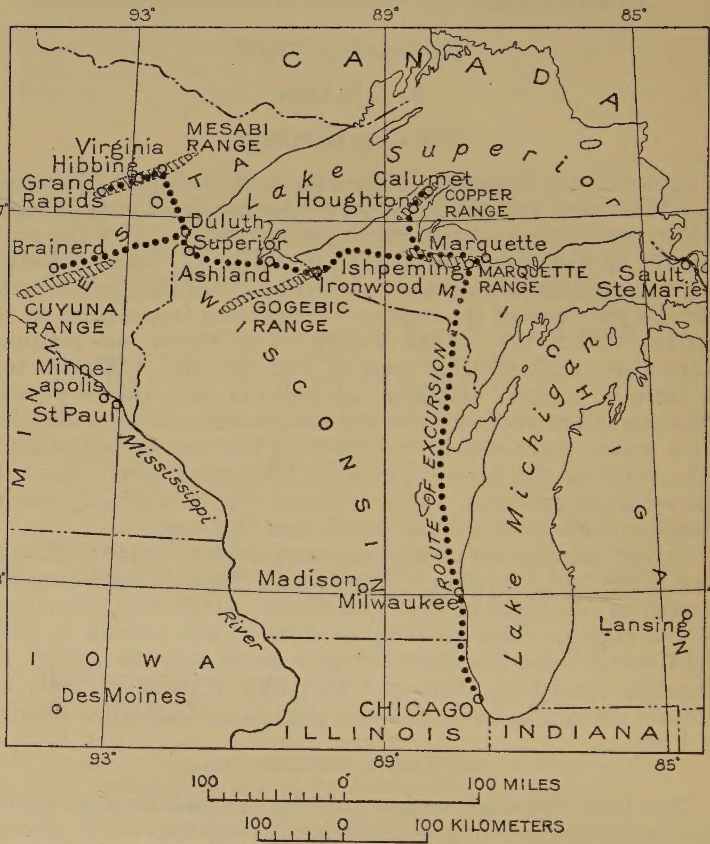


FIGURE 1.—Index map showing route of excursion

Geological Survey, are the outstanding ones. (See bibliography, pp. 18, 47.)

The pre-Cambrian succession now known represents a greater thickness of sediments and a longer time than all the post-Cambrian of North America. It represents at least four major unconformities, three periods of extensive plutonic intrusion, and three periods of mountain building. The record fades out below in a "basement complex" of igneous and sedimentary

rocks and their metamorphic equivalents. Special studies of this complex have resulted in the separation and better definition of geologic units, and this breaking up is likely to go further, adding large vistas to pre-Cambrian history. The lowest rocks yet known are like those of later times, except for metamorphism; there is no essential departure from "uniformitarianism," and there is nothing to indicate that pre-Cambrian sedimentation may not extend much further back than is indicated by the established record.

The accounts of the mineral ranges in this volume contain the details of the succession. Here only a very general summary is attempted for the region as a whole.

1. Cambrian: Beginning at the top, little-disturbed fossiliferous Upper Cambrian (St. Croixan) sediments mantle the peripheries of the region, with many inliers.

2. Keweenawan: Next below is the nonfossiliferous Keweenawan series, consisting of an immense mass, possibly 5 miles (8 kilometers) thick, of sandstone, with intercalated shales and conglomerates, containing in its lower part large quantities of extrusive lavas and intrusive laccoliths and sills. In degree of metamorphism it is more like the Cambrian than the underlying Huronian series. It has characteristic reddish, yellowish, and purplish colors and carries various evidences that it was essentially a continental deposit under semiarid conditions. Its lower part is tilted in marked unconformity to the Cambrian, but its upper part lies nearly if not quite parallel to the Cambrian. Obviously it was mainly deposited in an independent basin before the incursion of the Upper Cambrian sea. Although the Keweenawan is pre-Cambrian in the sense of preceding the Upper Cambrian transgression, having structural and igneous affiliations with the pre-Cambrian, and being nonfossiliferous, it may be Cambrian in the sense that it was being formed at the same time as Middle and Lower Cambrian sediments in distant Cambrian seas.

3. Huronian: Unconformably below the Keweenawan the metamorphic character of the rocks abruptly changes. They are hard and crystalline, locally schistose, are prevailingly gray and green, and conspicuously lack the reddish colors of the Keweenawan. On the whole they give more evidence of water deposition, though deposits of shallow water and deltas are also present. For convenience in reference these characteristics may be grouped under the general heading "Huronian type."

The uppermost Huronian group, which is also the thickest and most extensive, is slate locally called by different names (Virginia, Rove, Carlton, Tyler, Copps, Michigamme), occupying the largest area of all the pre-Cambrian sediments of the Lake

Superior region. The slate gives evidence of delta deposition. Near its base it locally carries intercalated iron formations (Bijiki, Deerwood, upper iron formations of the Crystal Falls and Iron River districts), contributing a minor part of the iron ores of Lake Superior. In places it contains basic sills and flows, and south of the Cuyuna district in Minnesota and in northern Wisconsin it is intruded, with the usual metamorphic results, by granites.

Beneath the slate comes the great iron formation of the Lake Superior region (Biwabik, Ironwood, Negaunee, Vulcan), represented in the Mesabi, Gogebic, Marquette, and Menominee districts and containing by far the greater part of the commercial ore. In part of Michigan a definite unconformity, with slight angular discordance, separates the iron formation from the overlying slates, but in Minnesota and Ontario this unconformity has not yet been proved, a fact which much complicates any statement of correlation. Conformably below the iron formation is a succession of quartzite and slate (Pokegama, Palms, Ajibik), usually less than 200 feet (61 meters) in thickness, but thicker in the Marquette district. These beds represent the beginning of the peculiar period that resulted in this unique iron formation. The iron formation and underlying quartzite may be tentatively called middle Huronian.

The upper and middle Huronian groups thus far described are widespread over the region, but the beds next below are more limited in their distribution. In Minnesota there is a banded siliceous slate series, with conglomerates, highly metamorphosed, called the Knife Lake series (lower-middle Huronian in Monograph 52), standing with conspicuous angular discordance from the overlying sediments. This formation carries evidence of continental origin. In Michigan and Wisconsin there is a ternary succession of quartzite (Mesnard, Sturgeon, and Sunday), dolomite containing algal textures (Kona and Bad River), and slate (Wewe), called lower Huronian in Monograph 52, well assorted, of water deposition, with definite unconformity but only slight angular discordance from the overlying sediments. The Michigan and Minnesota occurrences are separated by a distance of 150 miles (241 kilometers), and whether or not they are equivalent to each other is yet unknown. Under one interpretation, adopted by the United States Geological Survey, the Knife Lake series of Minnesota represent a continental equivalent of the water-deposited sediments in Michigan. The two have been further differentiated in appearance by folding and plutonic intrusion that affected the continental sediments to the north and not those to the south. An alternative explanation is that the Knife Lake series to the north are older and unconformably

below the water-deposited series to the south. The Doré series of the Michipicoten section northeast of Lake Superior has similarities of composition and structure to the conglomerate phases of the Knife Lake series of Minnesota and presents much the same problem of correlation with the known Huronian series to the south.

4. Basement complex: Underlying all the Huronian sediments, with marked unconformity, is a basement complex (called Archean), which has much the same group charactistics in all parts of the region. The oldest rocks of this complex are a great series of basaltic flows (Keewatin) intercalated with thin slate beds and with beds of iron formation, which is productive only in the Vermilion district of Minnesota. Intrusive into the Keewatin rocks are granites (Laurentian), of which several types and ages have been discriminated. It is possible even that some of the granites are really post-Laurentian in parts of areas assigned as a whole to the Laurentian.

In the Rainy Lake district, northwest of Lake Superior, there is apparently a larger mass of slates within and beneath the Keewatin flows than in other parts of the region. These have been given the local name Coutchiching. Some of the Coutchiching has been found to be equivalent to the Knife Lake, which is above the Keewatin, and there is still dispute on structural grounds as to the volume of slates really represented by the Coutchiching, and whether this volume is sufficient to warrant a separate name, in view of the well-known occurrence of slates within the Keewatin.

The unconformity above the basement complex has been emphasized by the United States Geological Survey as the principal break in the pre-Cambrian and as the dividing line between Archean and Algonkian rocks. In Michigan and Wisconsin it is much the most conspicuous unconformity. In Minnesota and Ontario, however, though definitely proved, it is overshadowed by the structural discordance at the top of the Knife Lake series. Some of the geologists approaching the region from the north side of Lake Superior have applied the name "Eparchean interval" to this later unconformity, classifying everything below it, including the Knife Lake sediments, as Archean. This fundamental difference of opinion, which is reflected in various classifications, tends to obscure the fundamental agreement upon the succession in individual districts. The question is simply whether the Knife Lake series shall be classified with the Huronian or with the pre-Huronian, and in the present state of knowledge this can be only a matter of opinion. In this guidebook it is called Huronian, in accordance with the classification of the United States Geological Survey.

CORRELATION

Correlation of the formations in the Lake Superior districts is complicated by the impossibility of tracing physical connections across intervening covered areas. It is complicated also by the fact that the several great periods of orogeny and plutonic intrusion have not affected all of the region equally. The first great period of folding and intrusion was that of the Laurentian, which seems to have been widespread. The next period, that of the Giants Range or Algoman intrusion and folding, is registered only in the Knife Lake (and equivalent) groups to the north and northeast of Lake Superior, without any known expression to the south. The third period (post-Huronian) affected the upper Huronian and Keweenawan south of Lake Superior and left relatively undisturbed the upper Huronian and Keweenawan in Minnesota. The Lake Superior syncline dates mainly from this period. Thus it is that unconformities, when traced through the region, take on quite different structural aspects, and that ancient-looking metamorphic rocks in one locality may be really younger than less metamorphosed rocks elsewhere. Much of the confusion in regard to correlation has arisen from failure to comprehend these facts, and particularly to remember that there are three definitely proved periods of plutonic intrusion and orogeny rather than two. Enough facts are now known to give students of Lake Superior geology a clear picture of the succession of events for each district, but any attempt to compress these facts into a simple classification applicable to the whole region involves unproved assumptions or overemphasis on facts of one district at the expense of distortion of perspective. The classification used in this summary is given in tabular form below, with moot points indicated by question marks:

Upper Cambrian.
Unconformity.
Keweenawan (Cambrian or pre-Cambrian?).
Unconformity.
Huronian:
- Granite intrusion (Little Falls, Presque Isle, Killarney). May be as late as Keweenawan.
- Upper Huronian. Virginia (in part), Rove, Tyler, Copps, and Michigamme slates.
- Unconformity (known only in Michigan).
- Middle Huronian. Biwabik, Ironwood, Negaunee, and Vulcan iron formations, with quartzite and slate base.
- Unconformity.
- Granite intrusion. Giants Range or Algoman, north of Lake Superior only.
- Lower Huronian. Lower quartzite, dolomite, and slate of the Marquette, Menominee, and Gogebic ranges. Knife Lake series of Minnesota (Huronian or pre-Huronian).

Unconformity (Eparchean interval).

Basement complex (pre-Huronian or Archean):
  Granite intrusion (Laurentian).
  Keewatin effusives with minor sediments.

As the correlation in Monograph 52 of the United States Geological Survey is the most widely known, it may be used as a basis for indicating changes introduced into the present classification. The upper Huronian (or Animikie) of Monograph 52 is now restricted to an undetermined part of the slates of this series in Minnesota and the Copps and Tyler slates of the Gogebic district. It includes, as before, the Michigamme slate and Goodrich quartzite of the Marquette range. The immediately underlying iron formation (Biwabik, Ironwood, Negaunee) is called middle Huronian. The Biwabik and Ironwood were formerly called upper Huronian. This change in classification arises mainly from the discovery of the unconformity of the iron formations with the overlying slates in the Gogebic and Menominee districts, which has resulted in a definite correlation of the iron formation of the Gogebic, Marquette, and Menominee ranges. The United States Geological Survey has in preparation a new map of the Lake Superior region, with discussion of these later developments. The next underlying series is the lower Huronian of Michigan and Wisconsin, the same as before. The Knife Lake series, formerly called middle-lower Huronian, can now be called lower Huronian or pre-Huronian, depending on what interpretation is given to the alternative possible relation to the lower Huronian rocks of the south shore. The basement complex (Laurentian and Keewatin) remains the same, unless the Knife Lake series is interpreted as belonging with it, in which case a marked unconformity is included.

For the ranges to be visited the correlation above set forth may be summarized in tabular form as follows:

	Michigan copper range	Marquette iron range	Gogebic iron range	Mesabi iron range	Cuyuna iron range
Post-Keweenawan.	Quaternary. Unconformity Upper Cambrian.	Quaternary. Unconformity Upper Cambrian.	Quaternary. Unconformity Upper Cambrian.	Quaternary. Unconformity Cretaceous.	Quaternary. Unconformity. Shale and conglomerate.
	Unconformity [a]	Unconformity	Unconformity	Unconformity	Unconformity.
Keweenawan.	Intrusion of gabbro and acid differentiates. Freda sandstone. Nonesuch shale. Great conglomerate and Lake Shore traps. Copper-bearing basic lavas and minor conglomerates.	Intrusion of basic igneous rocks and granite.	Basic lavas. Conglomerate.	Intrusion of Duluth gabbro.	Dikes and basic lavas.
			Unconformity	Unconformity	Unconformity.
Upper Huronian.		Michigamme slate with Bijiki iron formation and Clarksburg volcanics. Goodrich quartzite and conglomerate.	Presque Isle granite.[b] Tyler slate.	Virginia slate.[c]	Cuyuna group with Deerwood iron formation. Emily group. Aitkin formation.[d] Basal conglomerate.[d]
		Unconformity	Unconformity		

Middle Huronian.		Negaunee iron formation. Siamo slate. Ajibik quartzite.	Ironwood iron formation. Palms quartz slate.	Biwabik iron formation. Pokegama quartzite.
		Unconformity	Unconformity	Unconformity
Lower Huronian.		Wewe slate. Kona dolomite. Mesnard quartzite.	Bad River dolomite. Sunday quartzite.	Giants Range granite.[e] Knife Lake series.[e]
		Unconformity	Unconformity	Unconformity
Archean.		Laurentian granite. Keewatin.	Laurentian granite. Keewatin.	Keewatin.

[a] Possibly the Upper Cambrian and the Freda sandstone are conformable in the Lake Superior Basin.
[b] The Presque Isle granite may be Keweenawan.
[c] The lower part of the Virginia slate may belong with the Middle Huronian, because the existence and position of an unconformity between the upper and middle Huronian has not yet been established in Minnesota.
[d] The lack of a proved unconformity makes it impossible to decide whether the Cuyuna section is upper or middle Huronian.
[e] These may be pre-Huronian.

NATURE OF THE IRON FORMATIONS

The Lake Superior iron formations, like those in the pre-Cambrian elsewhere, represent a type and scale of sedimentation not known in post-Cambrian time. They now consist mainly of well-oxidized banded jaspers and ferruginous cherts. Before oxidation they contained, in addition to jasper, large masses of banded siliceous iron carbonate and greenalite rocks. Large parts of the iron formation have been anamorphosed into banded quartz-amphibole-magnetite rocks under the influence of igneous intrusion. The total area of iron formations at the rock surface is about 225 square miles (582 square kilometers). All are agreed that the iron formations are nonfragmental sediments, but there is difference of opinion as to the source of the solutions. The great difficulties in the way of explaining such solutions as the products of ordinary weathering and erosion have led United States geologists to consider favorably the possible contribution to sedimentary agencies from contemporaneous igneous sources. For some of the districts, like the Vermilion and Michipicoten, positive evidence of this hypothesis seems to be available. For others it is a hypothesis based only on the existence of contemporaneous though not always contiguous igneous effusions and on the inadequacy of normal sedimentary agencies to explain the facts.

The secondary concentration of Lake Superior iron formations to iron ore has consisted of oxidation of such of the original compounds as were ferrous and the leaching out of vast quantities of silica. The rock in about 6 per cent of the area of the iron formations, exclusive of anamorphic phases, has been altered to ore. The general relations of the ores to present and past erosion surfaces and to structural basins seem to demonstrate the agency of meteoric waters. On the other hand, the immense scale of the process and the fact that heat would so obviously accelerate it have led to a search for evidence of activity of hot waters. One hypothesis now being discussed is that hot waters may have come upward directly from the intrusions. If the overwhelming evidence of concentration of the ores in structural basins related to the surface is taken into account, contributions of heat, not juvenile waters, from igneous sources may be possible.

GEOLOGY OF THE MARQUETTE RANGE

By C. O. Swanson

The Marqette range is essentially a syncline of Huronian sediments that extends about due west from the city of Marquette, Michigan, for a distance of 30 miles (48 kilometers).

To the north and south are uplands that lie somewhat above the general level of the range and are composed mainly of granitic gneiss and greenstones.

GENERAL SUCCESSION AND STRUCTURE

The succession of the formations, from the top downward, is as follows:

Pleistocene: Glacial and fluvioglacial sediments.
Unconformity.
Cambrian: Fossiliferous upper Cambrian sandstone.
Unconformity.
Algonkian system:
- Keweenawan: Probably represented by greenstone and granite intrusives.
- Upper Huronian—
  - Michigamme slate, with Clarksburg volcanics and Bijiki iron formation as local members.
  - Goodrich quartzite.
- Disconformity.
- Middle Huronian—
  - Negaunee iron formation.
  - Siamo slate.
  - Ajibik quartzite.
- Unconformity.
- Lower Huronian—
  - Wewe slate.
  - Kona dolomite.
  - Mesnard quartzite.
- Unconformity.

Archean system:
- Laurentian: Granite and syenite intrusives.
- Keewatin: Greenstone.

The pre-Cambrian formations of the Marquette range (pl. 1) form a synclinorium, with a westward pitch at its east end, so that the outcrop of each formation has the general shape of a crenulated U opening westward. The Cambrian sandstone is horizontal and occurs as small outliers of the Paleozoic that covers large areas to the south and east. The Pleistocene forms a nearly continuous mantle over all the older rocks.

ARCHEAN SYSTEM

The rocks which practically all observers consider to be Archean lie at the base of the north limb of the Marquette synclinorium. They consist of the Keewatin series and the Laurentian intrusives into it.

The Keewatin is mainly a series of basic lavas, pyroclastic rocks, and associated intrusives, which, through alteration and dynamic metamorphism, have become greenstone schists. The series also includes a minor amount of acid volcanic and intrusive rocks and sedimentary rocks such as reworked volcanic material

and highly ferruginous sediments similar to parts of the Negaunee iron formation.

The Laurentian series is composed principally of schistose and gneissic granites which are intrusive into the Keewatin. Associated with the granites are small masses of syenite schist and gneiss, generally rich in hornblende or its derivatives.

ALGONKIAN SYSTEM

Lower Huronian.—The lower Huronian is a conformable group of sediments which has been divided into three parts—the Mesnard quartzite, the Kona dolomite, and the Wewe slate. All the beds have been highly metamorphosed and intricately folded and faulted. The lower Huronian is confined at present to the eastern part of the Marquette synclinorium. In the western part it was removed by erosion between lower and middle Huronian time.

The Mesnard quartzite has a basal conglomeratic member which, resting partly on the Keewatin and partly on the Laurentian, bears evidence of the long period of erosion that occurred between Huronian and Archean time. Above this basal member the Mesnard is composed of alternate members of quartzite, slate, and cherty sediments.

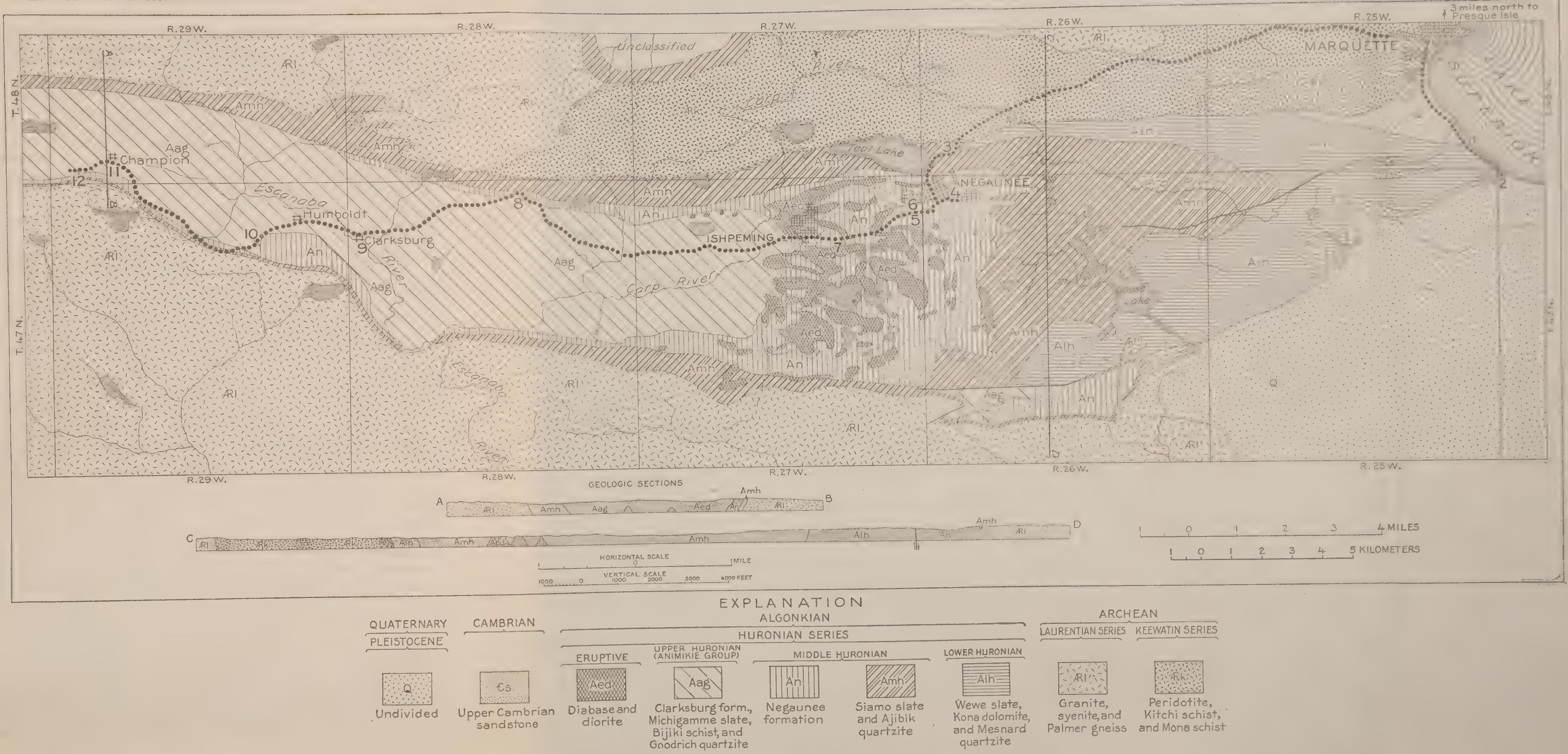
The Kona dolomite is typically a cherty dolomitic marble. Interstratified with this rock, however, are layers that were originally argillaceous and sandy.

The Wewe slate, originally a fine to sandy mud, is now mainly a slate with interlaminated beds of graywacke and quartzite.

Middle Huronian.—The middle Huronian is subdivided into the Ajibik quartzite, the Siamo slate, and the Negaunee iron formation, all conformable. In the south and west the slaty Siamo facies is thin or absent.

The basal Ajibik quartzite truncates the lower Huronian in the eastern part of the area, lying successively on Wewe slate, Kona dolomite, and Mesnard quartzite as it is traced westward. Farther west the lower Huronian is missing, and the Ajibik rests on the Archean. Peneplanation between lower and middle Huronian time is indicated by the fact that the lowest Ajibik beds extend obliquely across the strata of the Mesnard quartzite and other formations without any interruption or rapid change in character.

The Siamo slate is in general poorly exposed. It is mainly a thin-bedded slate with scattered layers of quartzite or graywacke. In the eastern part of the area, where it is thickest, it contains a lens of iron formation similar to the Negaunee, and at its top it contains ferruginous laminae. In the extreme western part of the area it is largely a mica schist.



GEOLOGIC MAP AND CROSS SECTIONS OF THE MARQUETTE RANGE

From U. S. Geol. Survey Mon. 52, pl. 17, 1911.

The Negaunee iron formation is the principal ore-bearing rock of the Marquette range. It lies conformably upon the Siamo or Ajibik, but its upper surface is sharply marked by the unconformity at the base of the Goodrich. The irregularity of this surface causes great variations in the thickness of the iron formation. In general, the Negaunee is thickest in the vicinity of Ishpeming and Negaunee and thins to the west. Beyond Humboldt, on the south limb, and Dexter, on the north, the iron formation is present only intermittently. Lithologically, the Negaunee can be subdivided into three main types—Cherty carbonate, which is simply the original sediment recrystallized by dynamic metamorphism; ferruginous chert, which is oxidized cherty carbonate; and magnetite-grunerite rock, which is the original formation recrystallized under contact-metamorphic conditions. These types and various subdivisions of them are described in more detail below, in the section on ore deposits.

Upper Huronian.—The basal portion of the upper Huronian is mainly coarsely clastic and is called the Goodrich quartzite. The bottom is conglomeratic, and where it rests on the Negaunee it forms a typical jasper conglomerate, characterized by pebbles and boulders of jasper, together with chert, ore, and quartz.

Above the Goodrich the beds are mainly finely clastic and compose the Michigamme slate. In the east the formation is mainly gray slate and graywacke; in the west, mica schist and gneiss. On the south limb, near the base of the Michigamme, there is the local Clarksburg member, which consists largely of basic pyroclastic material, in places with conspicuous foreign fragments of granite and quartzite. Lithologically the Clarksburg is now mainly a chlorite schist. The Michigamme also contains a local iron formation member, called the Bijiki. There appear to be two horizons at which the iron formation occurs—one below the Clarksburg and one above. The lower bed is rather impure and contains some volcanic material. The higher bed is associated with highly graphitic slate and has produced a small amount of limonite ore. Like the Negaunee, these members show three principal metamorphic types—cherty carbonate, ferruginous chert, and magnetite-grunerite rock.

Keweenawan (?).—Both basic and acidic intrusives are found in the Huronian sediments. Most of them may be tentatively called Keweenawan.

The basic intrusives include a large variety of types, both as to composition and as to mode of occurrence. Probably some are of upper Huronian age, related to the Clarksburg volcanic rocks. Many of the larger bodies, however, follow planes of weakness developed during the deformation that affected the

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whole Huronian series and are therefore post-Huronian but earlier than Upper Cambrian. These larger bodies range from diorite to hornblende gabbro and occur as dikes, sills, and laccoliths.

Acidic intrusives are found in several places on the south limb of the syncline in the form of dikes of granite that cut rocks as young as the Goodrich. The granite is generally very coarse grained. Its content of dark minerals is usually restricted to a small amount of biotite. There are also present on both limbs dikes of felsite, which are probably related to this granite.

The extent of the post-Huronian granite is a subject concerning which various opinions have been expressed. According to one view the granite forms stocks or batholiths which have caused much metamorphism and deformation. At the other extreme is the conclusion that there is practically no post-Huronian granite in the area. An intermediate opinion is that the granite is present as small bodies representing local developments of magma.

CAMBRIAN SYSTEM

The Upper Cambrian sandstone is the only representative of the Paleozoic in this area. It occurs as small outliers with the bedding undisturbed and lies unconformably upon the lower Huronian and Archean near Marquette. The folding and metamorphism of the Huronian rocks are therefore of pre-Cambrian age. Elsewhere in the Lake Superior district the presence of boulders of iron ore in the Cambrian shows that much, if not all, of the ore concentration occurred before the Upper Cambrian was laid down.

QUATERNARY

There are no formations present in this area to represent the interval between the Cambrian and the Pleistocene. Probably Paleozoic beds up to the Devonian were once present, but all except a small part of the Cambrian have been removed by erosion. The Pleistocene deposits consist of till and fluvioglacial sand and gravel, which cover most of the bedrock surface.

GEOMORPHOLOGY

The larger topographic features are of preglacial origin. In general, the Marquette range is a valley carved in Huronian sediments, with the granitic complex forming uplands on each side. Within the valley, however, there are many ridges composed of the more resistant formations within the Huronian, such as quartzite beds, magnetite-grunerite formation, and intrusive sills.

The glacial deposits changed the details of the topography in many ways. The relief was reduced about half by deposition

in the lower parts of the area, where rolling morainal surfaces or flat sand plains were formed.

Since glacial time the streams have taken up the task of removing the glacial deposits. In general they follow their old courses, but in many places the glacial obstructions have caused them to cut new channels in the bedrock for short distances.

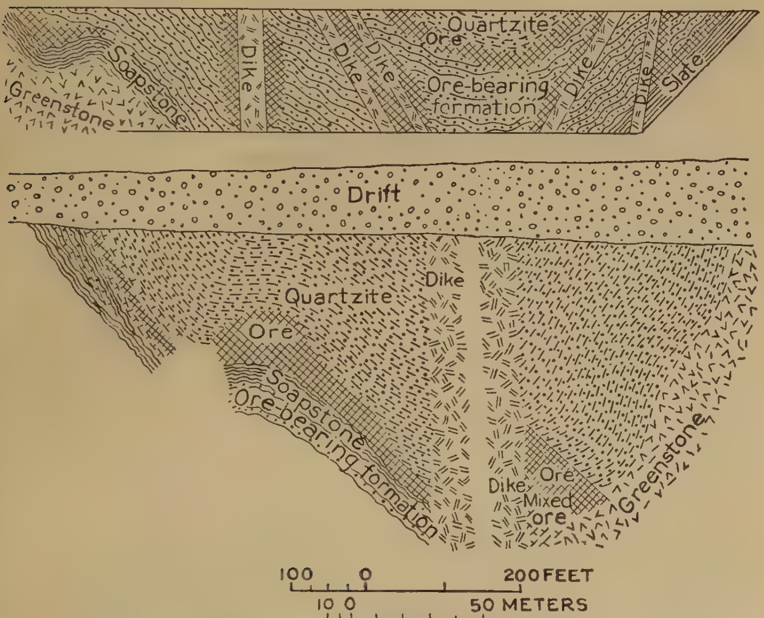

FIGURE 2.—Ore deposits of the Marquette district. (Both ore exploited and ore now in mine are represented as ore, as the purpose of this figure is to show the manner of the development of the ore rather than the present stage of exploitation.) Upper figure, generalized section in Marquette district; lower figure, cross section of Section 16 mine. (From U. S. Geol. Survey Mon. 52, fig. 36, 1911).

ORE DEPOSITS

In a broad way the ores can be divided into two geologic types, called soft ore and hard ore. For commercial purposes a subdivision of the soft ores, called siliceous ore, is also recognized. (See fig. 2.)

The history of the iron formations forms a most satisfactory basis for explaining the features of the various types of ore bodies.

The Negaunee, as originally laid down, was a chemical deposit composed mainly of chert and siderite, averaging 20 to 30 per cent Fe. Small amounts of iron oxide minerals were also present, and clastic materials, such as clay and sand, occurred in some layers, although in general they are more notable for their absence. The individual layers were mainly chert and sideritic chert and were mostly thin (less than an inch (2.5 centimeters) in thickness).

Before Goodrich time the iron formation was exposed to weathering, which, through oxidation of the siderite, formed large amounts of hematite or limonite and changed the formation to a ferruginous chert. Where the decomposition proceeded to its full extent most of the silica was also removed, leaving a soft ore consisting largely of hematite or limonite. The mechanical processes of erosion rearranged the surface mantle somewhat, removing it in places and depositing it elsewhere. Over much of the western part of the area the Negaunee was completely eroded at this time. In places, where the iron formation occupied low ground, it was oxidized only slightly, if at all.

Then followed the deposition of the Goodrich gravel and sand, which involved more rearrangement of portions of the surface mantle on the Negaunee. In places the lowest beds of the Goodrich were rich enough to be ore, and in places the sands were deposited on unoxidized iron formation—either the formation never having been oxidized, or the weathered and oxidized mantle having been removed.

The Michigamme clays and sands were next laid down upon the Goodrich. This deposition was interrupted by volcanic activity, forming the Clarksburg, and also by the deposition of the Bijiki formation both before and after the pyroclastic materials. The younger member of the Bijiki is associated with graphitic slate, suggesting swampy conditions.

The region was then folded and intruded by basic and acidic igneous rocks. The types of iron formation already in existence suffered various changes. Where dynamically metamorphosed, the original iron formation recrystallized to a similar rock, called cherty carbonate; the ferruginous chert formed jaspilite, containing specularite, dense hematite, magnetite, and jasper; and the soft ore was changed to hard ore. Where metamorphosed under contact conditions, the original iron formation recrystallized to a rock containing grunerite, magnetite, medium-grained chert, and, in places, garnet. The ferruginous chert and soft ore formed jaspilite and hard ore, just as under dynamic conditions, except that they acquired a coarser texture and more magnetite was developed.

A period of extensive weathering and erosion followed. Part of the iron formation was exposed. Only the cherty carbonate, however, suffered much decomposition, the jaspilite, hard ore, and magnetite-grunerite formation being very resistant. The cherty carbonate formed ferruginous chert and soft ore, just as the original iron formation did in pre-Goodrich time. The soft ore, representing the extreme stage of decomposition, was formed in places where the surface waters were most active, such as along faults and the axes of folds, because of greater brecciation there, and above impervious rocks, because of greater circulation there.

Cambrian and younger sediments were then laid down, and several periods of erosion occurred. These, no doubt, were accompanied by further decomposition and probably by the introduction of the gypsum and other minerals now found cementing parts of the ore. However, the bulk of the ore seems to have been formed before the Cambrian was laid down. All the factors that caused the extensive alteration at this time are not known, but apparently a considerable relief and dry climate were two of them.

The distribution of the ore deposits is readily described once their history is understood.

The deposits of soft ore are confined to the areas of ferruginous chert. In other words, there are none in the Negaunee in the western part of the range, because it is there a magnetite-grunerite formation. Stratigraphically, nearly all of the soft ore is in the Negaunee. A few deposits, however, lie in the Bijiki, which has its best development in the western part of the area.

Structurally, most of the bodies of soft ore occupy troughs. At the east end of the range there are several minor synclines that fold the footwall slate into troughs. Vertical dikes cutting the dipping footwall slate form troughs of another type. To the northwest are faults that strike obliquely to the trend of the footwall slate and cause an overlap in it. Some of them are followed by dikes, but all produce a third common type of trough. Within the Negaunee the basic sills aid in the development of similar troughs. In one type the top of a sill forms one side of the trough and a vertical fault contact with the sill the other side.

The deposits of hard ore are confined to the contact between the Negaunee and the Goodrich. Areally, they are not as restricted as the soft-ore bodies but occur through the whole length of the range.

The ore may be present as irregular pockets, as runs following a joint or dike, or as a fairly continuous sheet at or near the top of the Negaunee, or it may occur as a basal or interbedded con-

glomerate or fine-textured slate ore in the Goodrich. Structural and geomorphic conditions in pre-Goodrich time were no doubt the main factors controlling the position of the ore, although some alteration has occurred since. Ore bodies of this type may theoretically extend to great depths, and one of them, at Champion, has been mined to a depth of more than 2,000 feet (610 meters), with indications that it extends much farther.

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ITINERARY

Marquette lies at the east end of the range, on the shore of Lake Superior, which has an altitude of about 600 feet (183 meters). Within and near the town are many exposures of the Keewatin.

Presque Isle is about 3 miles (4.8 kilometers) north of Marquette. Near it, at the mouth of the Dead River, is an outcrop of Laurentian granite beside the road. This granite contains considerable chloritized hornblende, which is characteristic of the Laurentian in this range. At a small cove on the east side of Presque Isle a fault is shown. Northward across the cove the cliffs of peridotite are seen, and southward the horizontal Upper Cambrian sandstone that overlies the peridotite. On the southwest side of Presque Isle the contact of the sandstone with peridotite and granite may be examined. The highly weathered nature of the rocks beneath this old surface is well shown.

Mount Chocolay stands near the lake shore about 3 miles (4.8 kilometers) south of Marquette. A little north of it (1)[1] an outcrop of Mesnard quartzite, standing vertical, forms a small point and an island in the lake. This exposure shows minor faults, striking slightly oblique to the bedding, which cause some duplication and are illustrative of a larger displacement that causes a reappearance of this same member of the Mesnard at Mount Chocolay (2), where the contact of the lower Huronian with the Keewatin can be seen, as well as the complete succession in the Mesnard and Kona. Near the main road the exposures show

[1] Numbers in parentheses refer to Plate 1.

the transition from the vitreous Mesnard quartzite through slaty and dolomitic beds to the Kona cherty dolomite, the beds dipping steeply southward. Following the hillside southwestward, the route reaches the axis of a syncline, where the typical Kona cherty dolomite is exposed, exhibiting the so-called algal structure. Farther southwest the transition back to the vitreous Mesnard is encountered. In a quarry the vitreous Mesnard rests on the lower conglomeratic and slaty member of the Huronian, which in turn lies on Keewatin schist. Various dikes and veins can also be seen cutting the section, especially in the Keewatin in the southern part of the quarry.

Between Marquette and Negaunee (which lies 800 to 1,000 feet (244 to 305 meters) above and about 12 miles (19 kilometers) west of Marquette) the road follows the north limb of the synclinorium and passes scattered outcrops of Keewatin until a point (3) about a mile (1.6 kilometers) northeast of Negaunee is reached. Here the angular unconformity between the lower and middle Huronian is well shown where the road passes through a cut in a quartzite ridge. The northerly exposures on the ridge show Mesnard quartzite and slate, and the southerly ones the Ajibik, with a strike at a slight angle to that of the Mesnard. Just east of the road the basal Ajibik conglomerate can be seen as a thin plaster on a face of Mesnard quartzite. Above this conglomerate is a thin-bedded slaty quartzite, and above this in turn the vitreous quartzite of the Ajibik. A short distance southeast of the road cut a low ridge of Ajibik can be seen, and directly south of the road cut is the end of another low ridge composed of the Siamo formation. A fault striking parallel to the west ends of these two ridges causes the offset that is apparent in the Ajibik quartzite. The ridge of Siamo formation exposes slate with a few beds of quartzite and graywacke. The slate also contains some ferruginous laminae, which herald the appearance of iron formation above the slate. The outcrops give excellent illustrations of the relations between major and minor structural features, such as drag folds, small thrust faults, and the intersection of cleavage and bedding.

In the vicinity of Negaunee and Ishpeming, which lie adjacent to one another, the intrusive diorite forms many conspicuous knobs. In a general way these are parts of sills and outline the synclinal structure, but dikes and faulting have introduced many irregularities.

At the Athens location (4), southeast of Negaunee, the cherty carbonate or unoxidized phase of the iron formation is exposed. The glaciated outcrop shows the small extent of the oxidation of the cherty carbonate since glacial time. A small hill here

shows an anticlinal fold with a westward pitch, which is typical of the structure in this vicinity. Shafts of several soft-ore mines can be seen at this end of the basin. The ore bodies generally follow synclinal axes pitching westward.

Just west of Negaunee is the South Jackson open pit (5), where the ferruginous chert is exposed. This affords an excellent opportunity to study the character of the iron formation adjacent to a soft ore body, as the pit can be entered. The local trough is formed by a dike, which can be seen on the south wall of the pit. Veins containing barite and manganese minerals appear in the northeastern part of the pit.

Immediately to the north is another pit (6), which shows the typical jaspilite and hard ore. The unconformity between the Goodrich and the Negaunee is well exposed, dipping northward. Various structural relations of the hard-ore bodies are exhibited, such as conglomerate ore, pockets in the Negaunee beneath the Goodrich, and runs along dikes. It was here that ore was first discovered on the range, and a monument now marks the spot where the hard ore was found beneath a fallen pine tree.

Just east of Ishpeming is Jasper Hill (7), where the intricate folding of the brilliant jaspilite is well shown. South of Ishpeming are several mines in ore bodies that formed in troughs on the diorite, and to the north can be seen the concrete headframes of the Cliff mine, which follows the hard-ore horizon in the syncline under the town.

West of Ishpeming the highway enters the central part of the Marquette basin, which is underlain by the Michigamme slate, exposed in a few small outcrops. The road gradually swings over to the north limb, and about 7 miles (11 kilometers) west of Ishpeming the Dexter shaft (8) can be seen to the south. South of the shaft is a large outcrop of Goodrich quartzite, and north of the road ferruginous chert of the Negaunee iron formation is exposed on a low ridge. There are several mines on the north limb for 2 or 3 miles (3.2 to 4.8 kilometers) on both sides of this point. The ore bodies are mostly soft hematite, although some hard ore was also mined from the contact with the Goodrich. The soft ore is mainly on the footwall slate and follows troughs formed by faulting or dikes.

Westward from Dexter the road swings back to the south limb. At Clarksburg (9) the Clarksburg agglomerate is well shown, together with the underlying magnetic and gruneritic slates.

Leaving Clarksburg, the road crosses a hill through a cut in the Clarksburg formation and then swings around the north side of a large hill which is composed of Goodrich quartzite, magnetite-grunerite rock of the Negaunee, and greenstone

intrusives. Several old shafts and open cuts can be seen. From these was taken hard ore, which consisted of coarse specular schist and massive magnetite. A cut (10) on the main highway furnishes an excellent exposure of the Goodrich conglomerate.

The road then follows the south limb to Champion. On the hill (11) south of Champion the Clarksburg formation contains many large blocks of quartzite. The rock piles at the Champion mine (12) show coarse specular and magnetitic hard ore, jaspilite, and intrusive greenstone. South of the mine the magnetite-grunerite formation is exposed.

North of Champion there are a few old pits, from which was mined soft limonitic ore from the Bijiki iron-bearing member of the upper Huronian.

MINING ON THE MARQUETTE RANGE

By Franklin G. Pardee

It was only four years after the discovery of iron ore in the Lake Superior region, in 1844, that the Jackson Association mined the first ore from the Marquette range. The remains of the old furnaces that are left standing around the range are monuments to the early attempt to smelt the iron ore near the mines, charcoal being used to reduce the ore. It was not until the opening of the St. Marys Canal in 1855, however, that the iron-mining industry on the Marquette range got the start that has carried it to its present size.

According to the Lake Superior Iron Ore Association, 173,544,273 gross tons was shipped from this range to January 1, 1931. The largest annual shipment, amounting to 5,409,582 tons, went down the Lakes in 1916. The reserves of ore on January 1, 1931, as computed for tax returns, amounted to 58,194,000 tons, but this figure is below the expected ultimate production of the Marquette range, as there is still much unexplored territory that undoubtedly carries deposits of commercial value.

The three principal types of ore produced from the Marquette range are hard ores (magnetite and hard specular hematite), soft hematite ores, and siliceous ores. In the early days the production was limited to the hard ores, but at present only two mines are producing ore of this type. The siliceous ores account for about 20 per cent of the shipments.

The chemical analyses of the ores form the basis for another classification of the production from these mines. The following analyses show what was sent to the furnaces in 1931:

Grade	Shipment (tons)	Analysis		
		Native iron	Phos-phorus	Silica
Bessemer (phosphorus under 0.05 per cent)	190,410	54.54	0.038	11.00
Low-phosphorus non-Bessemer (phosphorus 0.05 to 0.18 per cent)	2,356,037	53.17	.105	8.01
High-phosphorus non-Bessemer (phosphorus above 0.18 per cent)	365,378	50.00	.313	8.25
Siliceous (silica 18 per cent or more)	688,803	37.38	.045	41.32
	3,600,628	49.90	.111	14.56

Grade	Analysis		Per cent of total
	Manganese	Moisture	
Bessemer (phosphorus under 0.05 per cent)	0.14	8.48	5.3
Low-phosphorus non-Bessemer (phosphorus 0.05 to 0.18 per cent)	.42	9.73	65.4
High-phosphorus non-Bessemer (phosphorus above 0.18 per cent)	.46	12.04	10.2
Siliceous (silica 18 per cent or more)	.09	2.90	19.1
	.35	8.59	100.0

The mining methods used on the Marquette range vary with the type of ore that is mined. The hard ores are extracted by some open room and pillar or stoping method, determined by local conditions. (See fig. 3.) The soft hematites are largely extracted by sublevel top slicing or some caving method, although there are a few soft-ore bodies that lend themselves to open stopes. The siliceous ores, except the small amount obtained in connection with underground operations, are all mined by open-pit methods.

The only property producing hard ore exclusively is the Cliffs-Shaft mine, at Ishpeming. Part of the workings are beneath the business portion of the town. The mine has a depth of about 1,000 feet (305 meters) and is served by two shafts whose concrete headframes are characteristic markers for it. The prop-

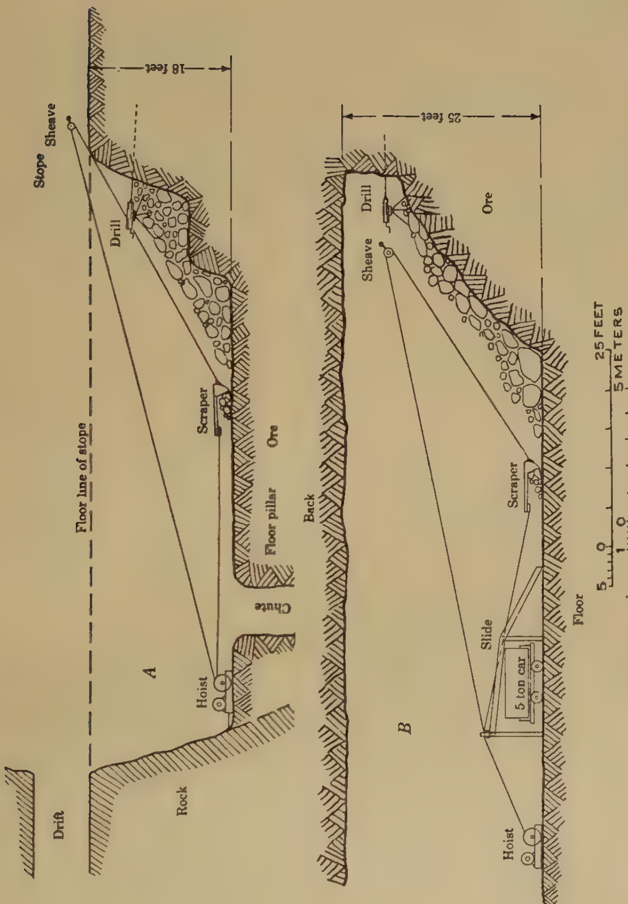

FIGURE 3.—Methods of mining hard ore on the Marquette range. *A*, Method of removing floor pillars; *B*, method of breast stoping. (From U. S. Bur. Mines Information Circ. 6138, fig. 6, 1929)

erty has been thoroughly described by Eaton (4),[1] and the costs given below are taken from his report:

Underground costs per long ton of ore hoisted at Cliffs-Shaft mine, 1928

[Ore hoisted during period, 420,000 long tons. Mining method, open stopes with pillar support]

	Labor	Supervision	Compressed-air drills and steel	Power
Development:				
In ore	$0.027	$0.004	$0.015	--------
In rock	.080	.009	.030	--------
Mining	.514	.028	.104	$0.006
Transportation (underground)	.142	.007	--------	.042
General underground expense	.075	.007	.004	.060
	.838	.055	.153	.108

	Explosives	Timber	Other supplies	Total
Development:				
In ore	$0.009	$0.003	$0.009	$0.067
In rock	.022	.003	.007	.151
Mining	.105	.002	.011	.770
Transportation (underground)	--------	.005	.048	.244
General underground expense	--------	--------	.034	.180
	.136	.013	.109	1.412

Representative operations at the soft-ore mines in the Marquette range are also thoroughly described by Eaton (5) and Graff (7). (See figs. 4, 5.)

Some method of mining that will cave the surface, generally the top-slicing system, is used wherever practicable, but in some mines water in the overburden, or some other condition, makes it necessary to support the surface. The mines range in depth from a few hundred feet to 2,500 feet (762 meters), which is about 1,000 feet (305 meters) below sea level. Most of the mines are wet, and pumping is an important item in the cost of mining. The following table shows the principal costs for mining a ton of soft ore:

[1] Numbers in parentheses refer to bibliography, p. 29.

Underground costs per long ton of ore hoisted at a soft-ore mine in the Marquette range, 1929

[From U. S. Bur. Mines Information Circ. 6380. Ore hoisted during period, 555,919 long tons. Mining method, top slicing]

	Labor	Supervision	Compressed-air drills and steel	Power
Development:				
In ore	$0.019	$0.001	$0.003	--------
In rock	.013	.001	.002	--------
Mining	.421	.018	.095	$0.008
Transportation (underground)	.126	.004	--------	.049
General underground expense	.020	.006	--------	--------
Surface expense applicable to underground operations	.004	--------	--------	--------
	.603	.030	.100	.057

	Explosives	Timber	Other supplies	Total
Development:				
In ore	$0.004	$0.003	$0.002	$0.032
In rock	.003	--------	.001	.020
Mining	.055	.079	.063	.739
Transportation (underground)	--------	--------	.031	.210
General underground expense	--------	--------	.064	.090
Surface expense applicable to underground operations	--------	--------	--------	.004
	.062	.082	.163	1.095

The pits in siliceous ores are at the south end of the district. These ores are used to furnish the required silica to some furnace charges, and they must be mined very cheaply in order to compete with other sources of silica. Open-pit methods with modern heavy-duty machinery are necessary to handle this hard abrasive material. Large-scale blasting is a common practice, and often a full season's shipment is broken at one time. The following table gives the average costs in the pits producing ore of this class, and the table on page 27 gives the average costs in underground mines.

Average costs per ton in open pits producing siliceous ores

	1929		1930		5-year average	
Cost of mining:						
Labor	$0.1682		$0.1364		$0.1767	
Supplies	.2321		.2712		.2682	
		$0.4003		$0.4076		$0.4449
Deferred mining cost		.0334		.0349		.0429
Taxes		.0418		.0694		.0521
General overhead:						
Office, superintendence, insurance, and contingent	.0415		.0398		.0527	
Depreciation	.1130		.0806		.0959	
		.1545		.1204		.1486
Transportation:						
Rail freight	.6518		.6750		.6852	
Boat freight	.7413		.7253		.7301	
Cargo insurance	.0009		.0016		.0021	
		1.3940		1.4019		1.4174
Marketing:						
Selling and operating commissions	.0890		.0879		.0858	
Analysis	.0094		.0058		.0064	
		.0984		.0937		.0922
Total ore cost		2.1224		2.1279		2.1981
Lake Erie value per ton		2.2849		2.3081		2.2998
Gross ore profit [a]		.1625		.1802		.1017
Other ore costs:						
Royalty		.0834		.0905		.1001
Interest on borrowed money		.0017		.0008		.0066

[a] This figure does not represent true profit, as much ore is sold at a discount.

Average costs per ton in underground mines on the Marquette range

	1929		1930		5-year average	
Cost of mining:						
Labor	$0.9785		$0.9704		$1.0665	
Supplies	.6339		.6067		.6264	
		$1.6124		$1.5771		$1.6929
Deferred mining cost		.0927		.0727		.0776
Taxes		.2501		.2437		.2786
General overhead:						
Office, superintendence, insurance, and contingent	.1730		.1216		.1427	
Depreciation	.1006		.0993		.0946	
		.2736		.2209		.2473
Transportation:						
Rail freight	.6600		.6788		.6726	
Boat freight	.7288		.7215		.7231	
Cargo insurance	.0023		.0027		.0026	
		1.3911		1.4030		1.3983
Marketing:						
Selling and operating commissions	.0896		.0828		.0856	
Analysis	.0056		.0088		.0073	
		.0952		.0916		.0929
Total ore cost		3.7151		3.6090		3.7876
Lake Erie value per ton		4.8394		4.7881		4.6963
Gross ore profit [a]		1.1243		1.1791		.9087
Other ore costs:						
Royalty		.1537		.1498		.1520
Interest on borrowed money		.0132		.0071		.0166

[a] This figure does not represent true profit, as much ore is sold at a discount.

The competition in the iron and steel business is reflected in the production of the raw material. This competition has been intensified during the last few years, and the mining operations have met this need for lower-cost ore by many methods. The

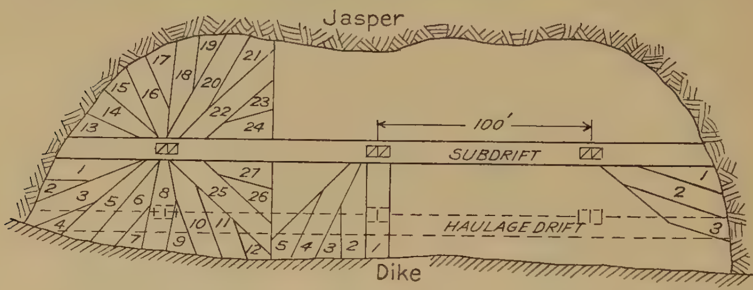

FIGURE 4.—Top-slice mining method used on the Marquette range. Shows radial slicing. (From U. S. Bur. Mines Information Circ. 6179, fig. 5, 1929)

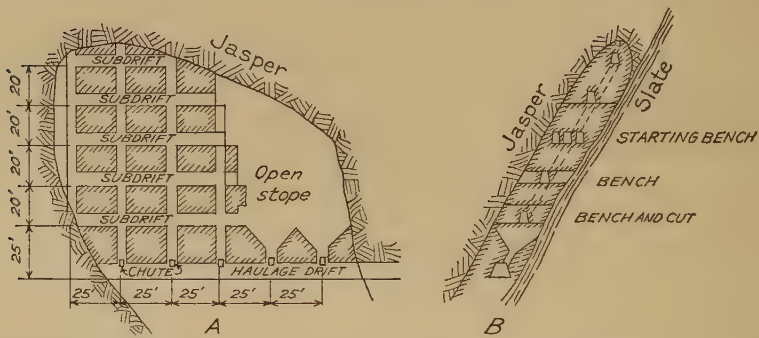

FIGURE 5.—Substope mining method used on the Marquette range. *A*, Longitudinal projection; *B*, Cross section. (From U. S. Bur. Mines Information Circ. 6179, fig. 6, 1929)

use of the scraper for handling ore and rock has been a large factor in the reduction of costs.

The following statistics give the results of Michigan iron-mining operations and show the progress that has been made in this industry during the last few years.

Summary of Michigan iron-ore production, 1926-1930
[Includes underground and open-pit mines]

	1926	1927
Ore mined...tons..	15,246,932	15,129,164
Ore shipped...do....	16,810,160	14,518,480
State and local taxes paid by active mines:		
Total...	$3,679,316.00	$3,882,061.58
Per ton mined...	$0.2413	$0.2566
Average number of days worked...	278	281
Average number of men employed...	11,302	10,792
Average daily wage...	$4.856	$4.761
Average yearly earnings per man...	$1,350.22	$1,337.84
Output per man per day...tons..	4.85	4.98

	1928	1929	1930
Ore mined...tons..	13,699,017	15,227,231	13,541,168
Ore shipped...do....	14,332,872	16,889,448	11,157,480
State and local taxes paid by active mines:			
Total...	$3,404,425.48	$3,436,058.17	$3,514,532.91
Per ton mined...	$0.2485	$0.2260	$0.2595
Average number of days worked	282	288	287
Average number of men employed...	9,206	8,996	8,554
Average daily wage...	$4.704	$4.915	$4.997
Average yearly earnings per man...	$1,324.18	$1,415.52	$1,436.55
Output per man per day..tons..	5.26	5.87	5.49

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GEOLOGY, EXPLORATION, AND MINING IN THE MICHIGAN COPPER DISTRICT

By T. M. Broderick

The material presented below is largely condensed from other articles and publications to which the geological department of the Calumet & Hecla Consolidated Copper Co. has contributed.

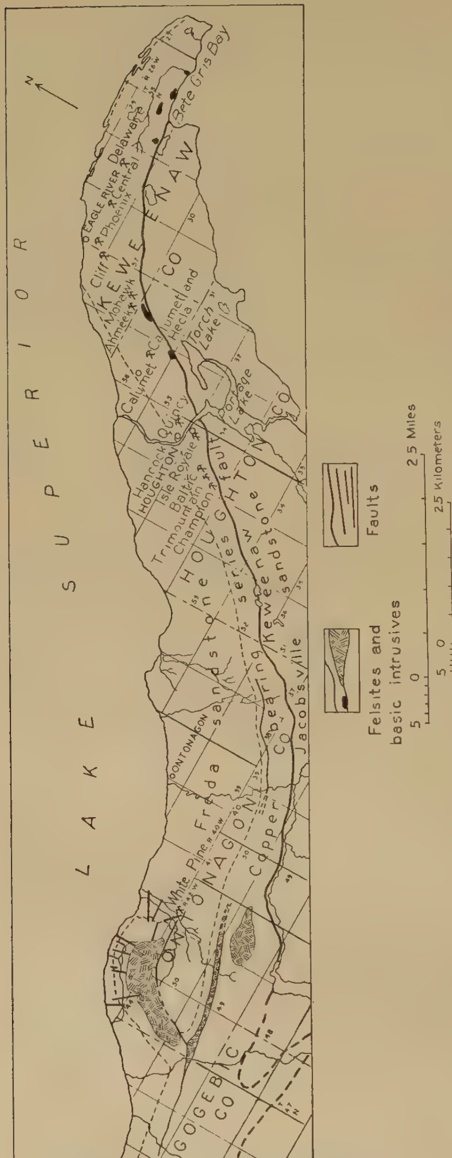


Figure 6.—Map of Copper Range. (From Min. Cong. Jour., October, 1931, p. 480)

Much of it was published in its present form in a paper by Broderick and Hohl (11).[2] The writer is indebted to C. H. Benedict for the paragraphs on milling and to H. C. Kenny for those on smelting. The statements made herein present the situation as it appears in October, 1931, the date of writing.

GEOGRAPHY

The mines in the copper district of Michigan lie within a narrow belt from 2 to 4 miles (3.2 to 6.4 kilometers) wide and more than 100 miles (161 kilometers) long. (See figs. 6 and 7.) The central part of this belt, about 26 miles (42 kilometers) in length, has furnished more than 95 per cent of the total production of the district. By far the greater part of this has come from mines in Houghton County. Keweenaw County, to the north, ranks second, but the production from Ontonagon County, to the south, has been very small.

The most prominent topographic feature of the district is

[2] Numbers in parentheses refer to bibliography, p. 47.

a narrow flat-topped plateau rising to a general level of 500 to 600 feet (152 to 183 meters) above Lake Superior and cut through by several low transverse valleys. This plateau extends in a northeasterly direction and projects into Lake Superior as Keweenaw Point.

The chief industry of Houghton and Keweenaw Counties is mining. The smelting is all done in Houghton County. Lumbering was formerly of importance but has declined as the original timber has been removed, while agriculture and dairying have been gradually expanding.

The district has the advantage of Great Lakes transportation and is also connected with outside points by railroads and by good highways. By far the greater part of the power used in the district is generated from coal shipped in by boat. A small fraction of the electric power is generated by a hydroelectric plant on the Ontonagon River, and a similar contribution will be made by a plant now being erected on the Sturgeon River.

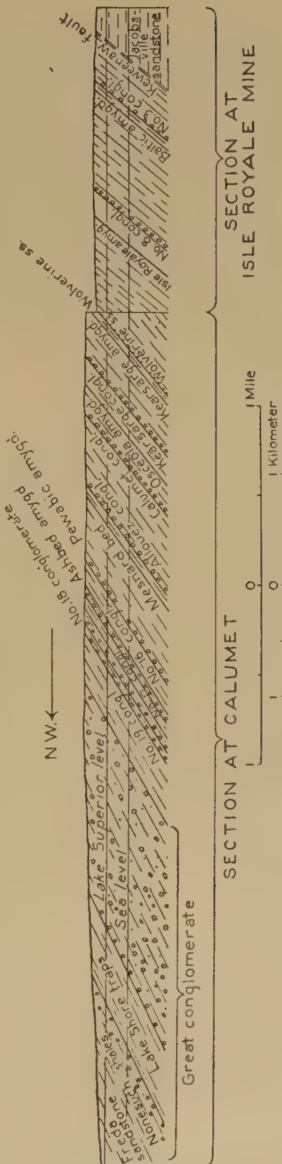


FIGURE 7.—Cross section through Copper Range. (From Min. Cong. Jour., October, 1931, p. 480)

GEOMORPHOLOGY

The area underlain by the Keweenawan traps forms a long, narrow plateau with small monadnocks rising above the general level and, especially toward the northern and southern parts of the district, with long monoclinal ridges and longitudinal valleys between them, which were formed by the erosion of the alternate inclined beds of varying hardness. The sandstone and conglomerate areas that lie on both sides of the basalt plateau have been eroded to form the present lowlands near the lake shores.

These major preglacial topographic features were not materially changed during the glacial period. The old weathered rock surfaces were scoured off by the ice (pl. 2), and the topography was smoothed and rounded somewhat. The minor details of the surface are determined by the irregularities of a deposit of drift 200 feet (61 meters) or more in maximum thickness, which was laid down by the ice and glacial streams. This deposit seriously affects the ease of exploration and development of the copper deposits. In addition to the moraines and glacial-stream deposits are those formed by the lakes along the south margin of the ice. Several old beach lines formed by the glacial predecessors of Lake Superior are present, and the highest in the copper country is about 700 feet (213 meters) above the present lake level.

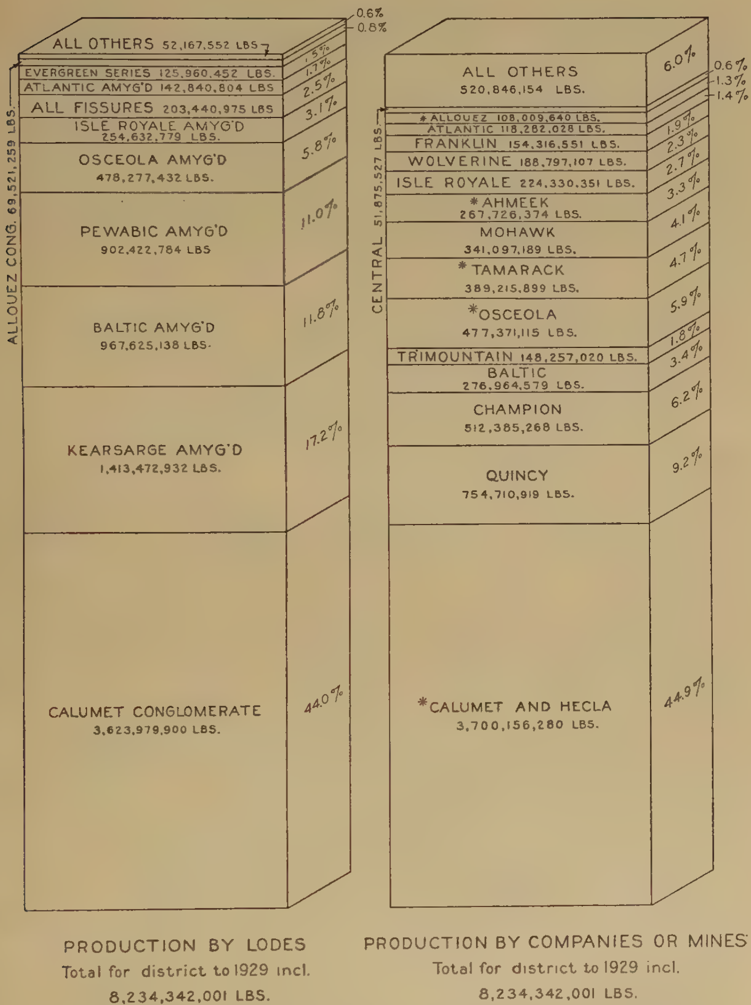
HISTORY

The mining of native copper in Michigan was started by a prehistoric race, whose ancient pits and trenches were found by the white explorers to have uncovered many of what subsequently proved to be the important deposits of the district. At the time of the visits of the first white men no mining was being carried on, and the Indians then living are said to have had no knowledge of the ancient workers. Among the earliest references to the existence of native copper are the records and maps of Jesuit priests who visited the district in the middle of the seventeenth century. A glacial boulder of native copper weighing nearly 2 tons was exposed on the bank of the Ontonagon River and attracted the notice of the early explorers until it was finally taken to Washington in 1843. In 1841 a report by Douglass Houghton, first State geologist of Michigan, aroused interest in the economic possibilities of the copper deposits, and explorations and developments by individuals and companies began. The first paying deposit was the Cliff fissure vein, discovered in 1845. Two other fissure veins were opened successfully—the Minesota in 1849 and the Central in 1856.

The first amygdaloid deposits to be worked were on the Isle Royale and Pewabic lodes, the former opened in 1852 and the latter in 1856. The Calumet conglomerate deposit was discovered in 1864, followed by the Osceola and Kearsarge lode discoveries 10 years later. The most recent discovery was the Baltic lode, in 1882.

STATISTICS

The Michigan copper district is the second largest producer of copper in the world, having produced 8,234,342,000 pounds (3,735,035,300 kilograms) of copper and paid $325,017,047 in



* *Calumet and Hecla production includes production from Tamarack mine since acquisition in 1917 and Osceola, Ahmeek, Allouez, and North Kearsarge mines since consolidation in 1923, also copper reclaimed from old conglomerate tailings.*

FIGURE 8.—Production of copper in Michigan copper district to end of 1929. (From Min. Cong. Jour., October, 1931, p. 478)

dividends from the beginning of mining operations in 1845 to the end of 1929. (See fig. 8.) About 44 per cent of the copper is to be credited to one ore body, the Calumet conglomerate; 48.9 per cent was obtained from five amygdaloid ore bodies—the Kearsarge, Baltic, Pewabic, Osceola, and Isle Royale. The fissure deposits, so important in the early history of the district and so interesting geologically, have contributed less than 2.5 per cent of either the total copper produced or the dividends paid. The district produced in 1929 a total of 186,393,836 pounds (84,546,592 kilograms) of refined copper, which was distributed among the various lodes and companies as shown in the following table:

Refined copper produced in Michigan copper district in 1929, in pounds

[1 pound equals 0.4536 kilogram]

Company	Calumet conglomerate	Kearsarge amygdaloid	Baltic amygdaloid	Osceola amygdaloid	Isle Royale amygdaloid	Pewabic amygdaloid	Ahmeek fissure	Total
Calumet & Hecla Consolidated:								
Mine	35,377,000	35,744,025		18,237,000			960,975	123,830,000
Tailings reclamation	33,511,000							
Copper Range:								
Champion			20,660,701					24,197,316
Baltic			2,127,926					
Trimountain			1,408,689					
Mohawk		20,043,127						20,043,127
Isle Royale					10,864,085			10,864,085
Quincy						4,459,426		4,459,426
Seneca		2,999,882						2,999,882
	68,888,000	58,787,034	24,197,316	18,237,000	10,864,085	4,459,426	960,975	186,393,836

GENERAL GEOLOGIC FEATURES

In Keweenawan time some hundreds of basaltic flows were extravasated, forming a series thousands of feet in thickness. Interbedded with the flows are felsite conglomerates, subordinate to the flows in number and thickness in the middle of the series but abundant and thick in the lower and upper parts. Interbedded with the traps in a few places are felsite and quartz porphyry flows, and the whole series is intruded by bodies of gabbro and associated acidic differentiates ranging in size from small masses, such as Mount Bohemia in Michigan, to the great Duluth gabbro of Minnesota. These intrusives are especially abundant toward the base of the series on both limbs of the Lake Superior syncline. The largest one, the Duluth gabbro, lying along the plane of unconformity at the base of the Keweenawan, is about 10 miles (16 kilometers) in thickness and forms a tabular body dipping with the overlying lavas toward the center of the syncline. Thus the series has a large intrusive mass at its base, of which the smaller intrusives in the Michigan copper district are probably offshoots. The sediments are all thought to be land deposits derived from a source down the present dip, toward the center of Lake Superior. The intrusives are thought to have been derived from the same magmatic chamber as the flows.

Each lava flow, as it cooled, gave off great quantities of gas, which collected into bubbles and rose to the top of the flow, where most of it escaped. But as the flow became cooler it also became more viscous, and finally the gas bubbles were entrapped near the top, forming a cellular capping. (See pls. 3, 4.) Some of the entrapped bubbles flattened out horizontally and coalesced with other flattened vesicles. In many of the flows the vesicular crust was broken up into fragments by subsequent movement or by further explosive outbursts of gas from the still liquid interior of the flow. These fragments of shattered vesicular rock tended to pile up in irregular heaps on the tops of the flows. Later filling of the vesicles produced the amygdaloids, which are classified as cellular, coalescing, or fragmental, according to their physical condition. These amygdaloidal tops are distinctly red, and examination of polished sections, supported by chemical analyses, shows that there is a steady increase in hematite toward the tops of the flows. This hematite was formed by oxidation of the original iron-bearing minerals of the traps; it evidently took place at high temperatures, probably while the flows were solidifying, and was accomplished largely by the escaping gases, although atmospheric oxygen may have played a part.

Most of the flows followed one another so closely that there is no evidence of any erosion or normal weathering between them. Occasionally, however, there was an interval long enough to allow the surface to become broken up and to permit the finer sand thus produced to sift in between the larger fragments, forming what is known as the scoriaceous amygdaloid. If the interval was long enough and other conditions were favorable, felsitic débris was carried in and deposited on the weathered surface, forming a felsite conglomerate. Thus many (but not all) scoriaceous amygdaloids underlie conglomerates.

The structure of the district is rather simple. The large ore bodies so far found have all been on the Keweenaw Peninsula, which is on the south limb of the Lake Superior syncline. The beds dip to the northwest at increasingly flatter angles toward the axis of the syncline. They are cut off on the southeast by the Keweenaw fault, which is a thrust fault dipping nearly parallel with the beds and bringing the Keweenawan lavas and conglomerates on the northwest side against Cambrian sandstone on the southeast side.[3] There are numerous branches of this fault in the lower part of the series, and where the beds have transverse folds there are associated transverse fissures. Although there was probably considerable movement on the Keweenaw fault in late Keweenawan and Paleozoic time, the main structural features (such as the big syncline, the minor transverse folds, and numerous faults and fissures, including the Keweenaw fault) were well developed when copper deposition occurred.

ORE DEPOSITS

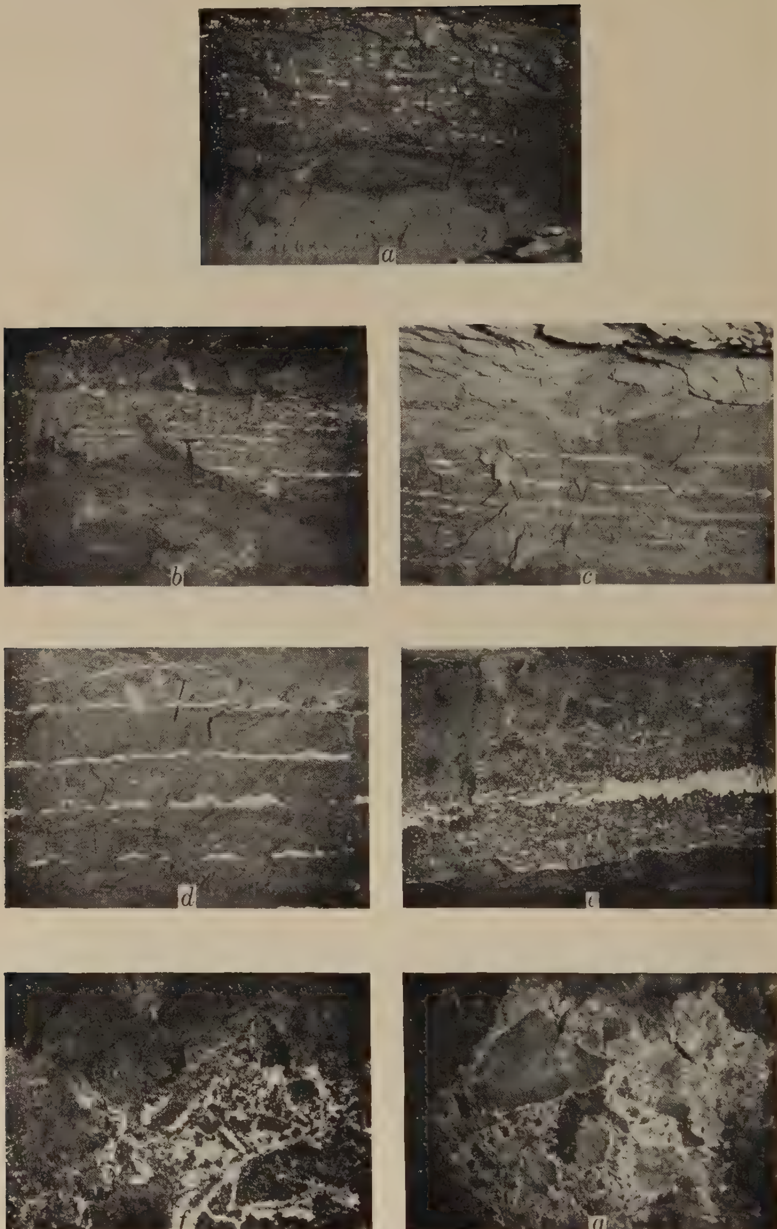
The six ore bodies that have yielded more than 90 per cent of the copper produced in the district (see p. 33) lie within the central portion of the series, which consists chiefly of lava flows. The ore mineral is native copper. Although native silver occurs in minor amounts, it is not usually separated from the copper in treatment. Both copper sulphide and arsenide also occur, but not in commercial amounts. (See fig. 9.)

The Calumet conglomerate ore body occurs in a felsite conglomerate; although known for many miles as a sedimentary stratum, for most of its known extent it is simply a thin sandstone or shale, in many places but a few inches in thickness. At Calumet, however, it opens out into a body from 5 feet (1.5 meters) to more than 20 feet (6 meters) in thickness and becomes much coarser, with many pebbles and boulders 6 or 8 inches (15 or 20 centimeters) in diameter and some much larger. This

[3] The usage of the United States Geological Survey is followed in classifying these formations as Keweenawan and Cambrian.

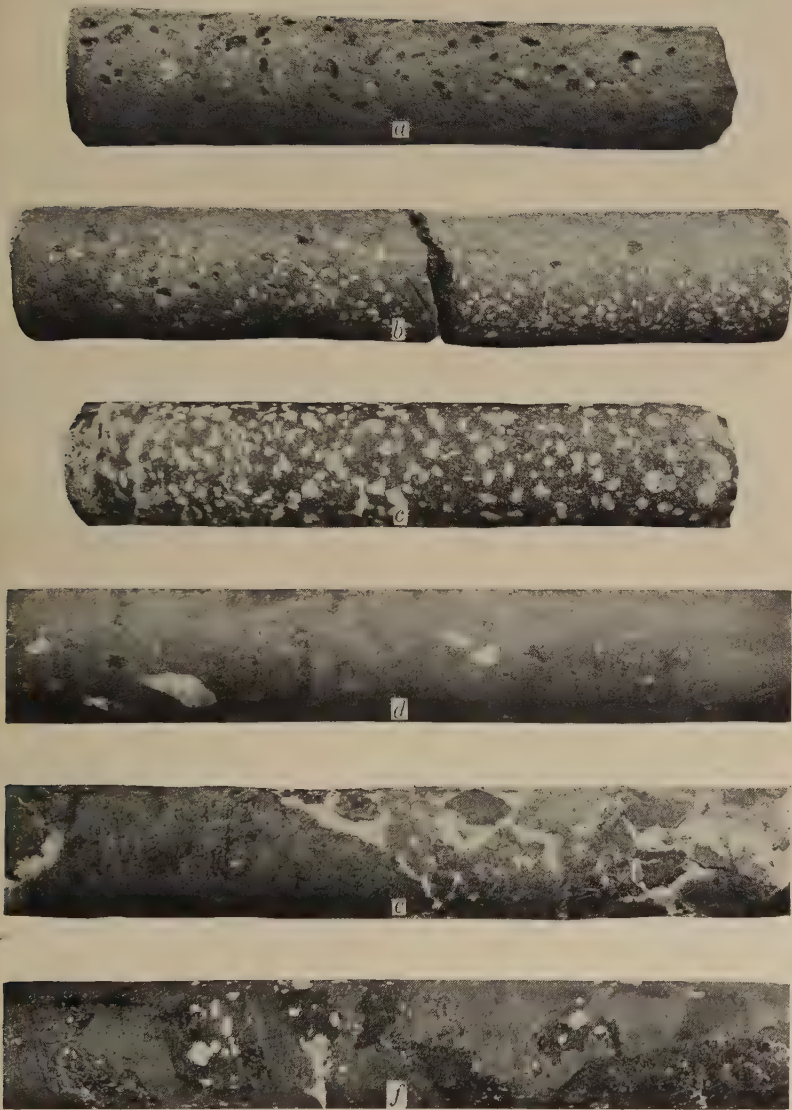
GLACIATED SURFACE SHOWING RESISTANCE OF AMYGDULAR INCLUSIONS

From U. S. Geol. Survey Prof. Paper 144, pl. 54, *C*, 1929.



TEXTURE OF FLOW TOPS AS SEEN IN LODES

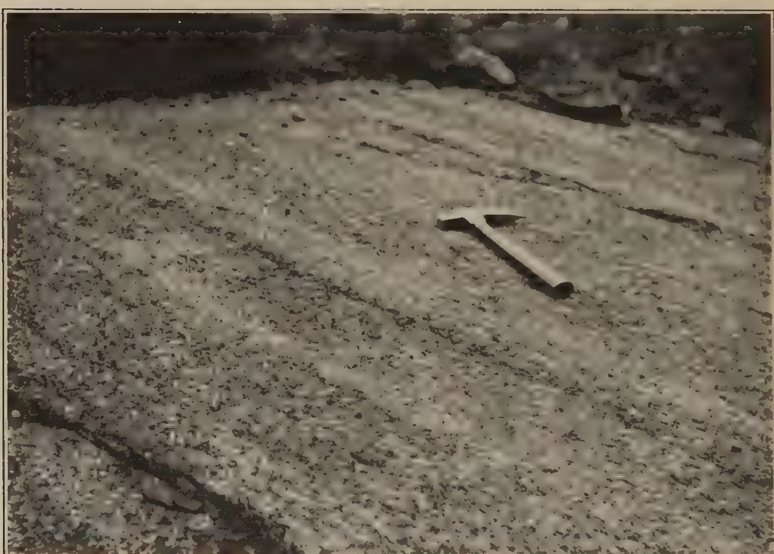
a, Cellular lode, tending toward coalescing; *b*, cellular lode, somewhat coalescing; *c*, coalescing lode; *d*, banded coalescing lode; *e*, strong band in coalescing lode; *f*, *g*, fragmental lode. From U. S. Geol. Survey Prof. Paper 144, pl. 58, 1929.



TEXTURE OF FLOW TOPS AS SEEN IN DIAMOND-DRILL CORES

a, *b*, Cellular amygdaloid, upper part; *c*, amygdaloid of glomeroporphyrite flow; *d*, cellular amygdaloid deep in amygdaloid; *e*, fragmental amygdaloid; *f*, scoriaceous amygdaloid or amygdaloidal conglomerate. From U. S. Geol. Survey Prof. Paper 144, pl. 60, 1929.

A. FLOW LAYERS OF PERIDOTITE IN GABBRO NEAR SHORT LINE PARK, DULUTH



B. FLOW LAYERS OF SLIGHTLY DIFFERING COMPOSITION IN THE MAIN MASS OF DULUTH GABBRO

conglomerate lens lengthens and thickens down the dip, and the copper is confined to this body, the depositing solutions apparently having been unable to penetrate the sandy or shaly margins that close in on the conglomerate lens like the sides of an inverted funnel. The copper, with adularia, epidote, calcite,

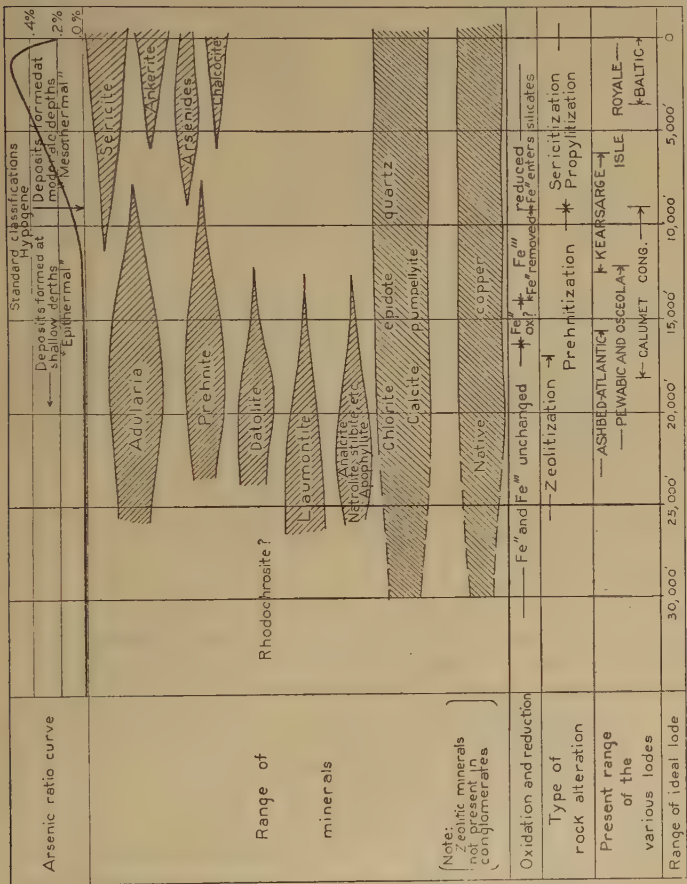


FIGURE 9.—Sequence of mineral deposition in Michigan copper district

and quartz, was deposited chiefly through replacement of the finer material between the pebbles. The richest mineralization occurred rather near the surface, where the solutions flowed through the more constricted portions of the lens. Zeolites or zeolitic minerals, such as datolite and prehnite, are not found in the Calumet conglomerate. The rock immediately associated

with the copper is bleached as a result of the removal of the primary hematite of the felsite pebbles and of the detrital hematite grains in the finer cementing material by the ore-depositing solutions.

The amygdaloid lodes are of a permeable type, because of their fragmental character, although the Pewabic amygdaloids are permeable in part because of the coalescing of the vesicles. None of the numerous cellular amygdaloids have been found to be copper bearing commercially. Minerals found in the amygdaloid lodes comprise a greater variety than those in the conglomerate lode, including quartz, epidote, chlorite, calcite, pumpellyite, adularia, sericite, ankerite, datolite, prehnite, and some zeolites. In most of these deposits there has been a rock alteration immediately associated with the deposition of the copper, which has resulted either in the total removal of the iron originally in the primary hematite of the lode or in its reduction to the ferrous state and incorporation in ferrous silicates.

The deposits differ in gangue minerals and character of rock alteration, and these differences have been regarded as peculiarities of the individual lodes. Zoning had been looked for, but the mineralogic changes in depth in even the deepest mines are inconspicuous. However, all the deposits carry minute amounts of arsenic. The ratio of arsenic to copper ranges in the different deposits from a few ten thousandths of 1 per cent up to 0.5 per cent. There is a corresponding variation in the small quantities of sulphur present, but there are more quantitative data on the arsenic. Deposits with similar arsenic ratios are found to have similar types of gangue minerals and rock alteration. The deposits with highest arsenic and sulphur ratios are characterized by a gangue of sericite and ankerite. Those with less arsenic and sulphur are characterized by an adularia-prehnite gangue. Those with the least arsenic are practically sulphur free and have increasing quantities of zeolites. These types of deposits are regarded as having been formed at successively lower temperatures in the order named and therefore represent different temperature zones. The three zones grade into one another, and commercial copper occurs in all of them. Calculations based upon the rate of increase in the ratio of arsenic to copper in depth indicate that commercial copper was deposited over a distance of more than 20,000 feet (6,096 meters) down the dip of the lodes. This estimate seems not unreasonable, inasmuch as mines like the Calumet & Hecla and Quincy already have followed copper about 10,000 feet (3,048 meters) down the dip and are still in ore.

Apparently among the conditions that an amygdaloid or conglomerate should have had in order to make an ore body were

the following: (1) It should have had access to the sources of the copper-bearing solutions in depth, either directly or indirectly, perhaps being fed by fissures that in turn made connections with the sources; (2) it should have offered a throughgoing solution channel—that is, it should have been a continuously permeable body as compared with the adjacent rock; and (3) there should have been suitable restrictions to the permeable portion. All the ore bodies are in relatively permeable rocks, but apparently some sort of a barrier was necessary to prevent the solutions from spreading out and dissipating their copper content in great bodies of noncommercial grade. Solutions ascending the Calumet conglomerate, for instance, were confined by the gradually converging shale margins. Those ascending the Osceola amygdaloid were deflected under long, raking bars of tight, cellular amygdaloid.

All the known ore shoots come to the rock surface somewhere with good copper content. There is no evidence of a leaching of copper at the surface with a redeposition at depth. As explained below, however, there is reason to believe that there may be undiscovered deposits in the district that do not reach the present surface, and the attempt to locate them is the object of exploratory work now in progress.

GENESIS OF THE DEPOSITS

There are two strongly contrasting theories to account for the native copper deposits. One is that cold, oxidizing chloride waters descended from the surface for many thousands of feet by gravity or by atmospheric pressure, first percolating through hot traps and gathering up disseminated copper, then carrying it laterally and downward into amygdaloids and conglomerates, where the solutions reacted with the ferrous silicates, forming native copper and ferric compounds. According to this theory, the traps are essential as sources of copper, the chloride waters are essential as carriers, and the deposits should be found on the upper sides of impermeable barriers.

The theory favored by the Calumet & Hecla geologists is that underlying intrusives known to exist in the Lake Superior Keweenawan, on crystallizing, gave off solutions rich in copper, arsenic, and sulphur; expelled under enormous pressures, they followed permeable amygdaloid and conglomerate channels upward, cooling and entering regions of lower pressure as they ascended; reacting with the highly oxidizing wall rock, they had their arsenic and sulphur oxidized by the ferric iron of the lodes and their copper deposited as native metal. According to this theory, the traps were not essential to the formation of the ore

bodies. The copper did not come from them, and any other oxidizing environment would have served to precipitate native copper, just as in Coro Coro, Bolivia, where there are no lava flows, and native copper was deposited in commercial quantities in red sandstones. The chloride waters now found in the Michigan mines are not regarded as being necessary to explain the native copper. The copper deposits should be found underlying impermeable barriers.

EXPLORATION

Most of the known amygdaloid and fissure deposits were found with copper showing in the outcrops. In some places a prehistoric race had mined the rock at the surface, and the white men later "rediscovered" the deposits by cleaning out the old pits. These prehistoric miners sometimes dug pits at convenient places to cache their copper: and by a strange coincidence, as the story goes, after one of these random caches containing amygdaloid copper had been cleaned out and deepened a few feet, it was found to lie directly over a part of the rich Calumet conglomerate ore body. There is some reason to believe that this pit was not simply a cache for the amygdaloid copper found in it, but that it actually encountered mineralized bedrock, because early accounts mention the fact that an amygdaloid in the immediate hanging wall of the conglomerate was found to be mineralized at this point. Thus by examination of the small percentage of the bedrock that is not thickly covered with glacial sand and gravel and by opening up the ancient miners' pits, the major ore bodies of the district have been found. The latest commercial ore body to be discovered was the one on the Baltic lode. Since that discovery, about 50 years ago, millions of dollars has been spent in diamond drilling, trenching, and underground work without discovering a new ore body. In the face of this long period of expensive exploration with negative results, what encouragement is there for further search for new ore bodies? Some of the considerations involved in exploration may be briefly reviewed.

Only a small percentage of the copper-bearing formation is not covered with drift, yet the examination of this small percentage led to the discovery of most of the amygdaloid and fissure ore bodies. Although the drift covering hampers exploration, the very fact that it is so widely present leads to the conviction that there must be undiscovered ore bodies beneath it. If the rock cropped out everywhere there would be little chance of finding new deposits exposed at the surface after 85 years of search.

Copper deposits are known to occur over an area of some hundreds of square miles. This is to be contrasted with other

districts, such as Butte, where a similar production has come from but a few square miles. Thus in this district the explorer is handicapped by the enormous areas of barren ground in the midst of which commercial deposits must be sought. On the other hand, it means just so many more square miles in which deposits may possibly occur.

There seems to be a generally accepted notion that enormous tonnages of rock exist with a copper content just below that required for a profit. The Ashbed and Allouez conglomerates are often mentioned as beds that are appreciably mineralized over large areas, because they are known to have some copper at widely spaced localities. Although the idea that higher prices for copper would increase the reserves of commercial ore is true to some extent, such an increase would by no means be as great as is generally believed. Experience in this district indicates that the rich deposits are large and the leaner deposits are smaller.

Although mineralogic studies have been a feature of all the geologic surveys of the district, nothing very positive of a mineralogic nature has been developed to serve as a guide in exploration. It is recognized, however, that the commercial lodes have a greater variety of minerals than the average amygdaloid. The recognition of the approximate position of a prospect in the zonal range by means of the arsenic ratio and characteristic gangue minerals is, of course, an advantage.

A study of surface geology is an inexpensive and necessary first step in exploration. It has resulted in the discovery of most of the deposits in the district and has furnished a fund of information on the general geology. The chances that any new deposits can be found by inspection of surface outcrops are exceedingly remote. Where the overburden is thin enough, trenching and test pitting may be used to advantage.

Diamond drilling is the most satisfactory method of determining the general geologic conditions, such as kinds of rocks and character and position of lodes, where any considerable depth of overburden exists. But it is not a reliable method of determining copper content because of the very erratic distribution of the metal. The drill may encounter local bunches of copper in a worthless lode; and on the other hand, in going through ordinary amygdaloid lodes of commercial grade, it is more than likely to miss the copper. Where the copper content is more uniformly distributed, as in a sandstone or conglomerate ore body, the drill has a better chance to obtain a good sample of it.

It was hoped that geophysical methods would be useful in the search for new deposits, but after a variety of electrical and

magnetic methods had been tried out the results were found to be disappointing. The copper is so small in amount and so widely disseminated that its effect on electrical methods is little or no greater than the effects caused by differences in thickness and character of overburden and in character of bedrock. There are no known magnetic effects connected in any way with the ore bodies. Various geophysical methods, however, are somewhat useful in preliminary geologic work, such as laying out diamond-drill locations. For such work the dip needle has so far been found to be satisfactory, as it affords a rapid method of determining the main features of the geologic structure. It could have been used to considerable advantage in earlier years in some places where the local strike was not so well known as it is at present. In recent years the Michigan Geological Survey has taken dip-needle readings over large areas of the copper-bearing formation for the purpose of studying the reliability of this method in mapping the details of stratigraphy and structure in the district.

After diamond drilling or any other method has done all that it can in determining the general geologic features of an area, actual undergroumd openings must be made to locate ore and to determine its grade. For every major lode deposit there are scores of erratic and local patches of mineralized rock scattered throughout the Keweenawan series, not only in Michigan but in the entire Lake Superior district. Only by opening up the lodes for hundreds or thousands of feet can it be determined whether or not the mineralization has produced ore of commercial importance; and large-scale mill-runs are necessary to determine the grade, ordinary sampling methods being useless because of the erratic nature of the mineralization.

It is apparent that the ore bodies are determined by favorable conditions of a purely local character, such as access to the source of solutions in depth, through-going permeability, and suitable restrictions by barriers. Even though the beds at a given horizon fulfill all the necessary conditions and include an ore body at one place, it would be purely a coincidence if beds at that same horizon in another place should be found to have the necessary conditions. Nevertheless, much of the exploratory work hitherto done in the district has been based upon the idea that if an ore body occurs at a certain horizon in one place it is likely that other ore bodies may be found at the same horizon elsewhere.

In recent years the method of exploration adopted by the Calumet & Hecla Consolidated Copper Co. has been to crosscut those parts of the series that, by diamond drilling or other means, are known to have exceptionally numerous beds of a favorable physical character. These crosscuts are driven from

conveniently located places in the mines or from shallow shafts sunk for the purpose. This method has an advantage over the old one in that numerous favorable beds are crosscut instead of one bed only—any individual bed, although having an ore deposit perhaps many miles away because of local favorable conditions, may be of a most unfavorable character at the place being explored. Even this improved method is unsatisfactory, however. It lacks definiteness in that it does not indicate specific places of outstanding attractiveness; furthermore, some of the known ore bodies are at the only favorable horizon for hundreds of feet in either direction. Therefore, the policy of exploring in belts of dominantly favorable amygdaloids would fail to find such ore bodies as occur in isolated favorable lodes.

Geologic studies during the last few years indicate more specific places to explore. A study of the relationships of lode mineralization and fissure mineralization has developed the idea that some of the fissures were mineralized by solutions that leaked away from the major amygdaloid or conglomerate channels. Especially would this have occurred if the lode were partly blocked off by the barriers closing in more or less completely, a condition in which the solutions might be able to make their way upward above such places only by escaping through the fissures intersecting the lode. In the few known examples where such a relationship between fissure and lode seems to exist, the copper does not continue on the fissure right down to the feeding lode but there is a gap of hundreds of feet of fissure vein in which there is not much copper. This situation leads to the speculation as to whether or not the old fissure veins that were so prominent in the early history of the district as producers of mass copper may not have been merely the vents for the solutions that escaped from some amygdaloid or conglomerate ore body at greater depth. These fissure deposits were worked to comparatively shallow depths, where they became too lean to mine; yet they continue downward as strong fissure veins filled with gangue minerals of a type which indicates that they are still high in the zonal range over which copper was deposited in this district. In order to test this idea, two of the old fissure-vein mines, the Cliff and the Phoenix, have been unwatered, and an attempt is being made to find a major amygdaloid or conglomerate deposit that may have acted as a feeder for the fissures. The chief elements of uncertainty, of course, are whether these particular fissures have such a relationship to a lode solution channelway, and, if so, whether that lode has been commercially mineralized and whether the gap between the bottom of the ore in the fissures and the ore in the lode is short enough to be bridged by a reasonable expenditure.

MINING

The ore bodies are tabular in form, average from 5 to 30 feet (1.5 to 9 meters) or more in thickness, and dip at angles of 30° to 72°. Where the operating company owns the outcrop, inclined shafts are sunk in the lode or close by in the footwall at intervals of about 2,500 feet (762 meters) along the strike. Some of these shafts are over 10,000 feet (3,048 meters) in length and reach vertical depths of over 6,000 feet (1,829 meters). For greater efficiency the Calumet & Hecla Co. is abandoning the inclined shafts above the 81st level. A haulageway 9,800 feet (2,987 meters) in length was driven at a vertical depth of 4,900 feet (1,494 meters) on the 81st level in an amygdaloid about 180 feet (55 meters) in the footwall of the Calumet conglomerate. The deep ore is raised to this level through inclined shafts by underground electric hoists and transported along the haulageway to a vertical shaft, in which it is carried to the surface. The vertical shafts sunk to mine the Calumet conglomerate have long been famous because of their great depths, one of them reaching a depth of over a mile (1.6 kilometers) below the surface. Vertical or steeply inclined shafts are also sunk in the hanging wall where a company does not own the outcrop of the lode. Such a shaft may be curved to swing into the lode when it is reached, or crosscuts may be driven to connect the shafts with the drifts on the lode.

Drifts are driven at intervals of 100 to 200 feet (30 to 61 meters) measured along the lodes. In most of the mines the drifts are driven to the boundary of the area to be operated from the shaft, and some variety of overhand stoping is used on the retreating system. The stopes in the Calumet conglomerate and the Osceola, Kearsarge, and Pewabic amygdaloid ore bodies are some modification of open stopes. The Isle Royale and Baltic lodes are too steep to permit work in an open stope without timber; in the Isle Royale shrinkage stoping is used; in the Baltic inclined cut and fill from sublevels.

Because the distribution of the copper is too erratic to permit sampling of the ordinary type, the stopes must be watched continually by the mining captains to avoid breaking rock of too low grade. Frequent mill reports are the sole guide other than the visual inspection of the stopes.

Underground temperatures are not extreme. For instance, the rock temperature on the Kearsarge lode at a vertical depth of 4,900 feet (1,494 meters) is 86.2° F.; on the Calumet conglomerate at a vertical depth of 5,502 feet (1,677 meters) it is 93.0° F. The mean annual temperature of the air at Calumet

is 39.4° F. The mines are comparatively dry, the Calumet & Hecla mine on the conglomerate lode having an average inflow for 1930 of 1,567 gallons (5,932 liters) a minute.

MILLING

Milling and metallurgical plants for all mines are located along either Lake Superior or some of the inland lakes tributary to it and are from 4 to 15 miles (6.4 to 24 kilometers) distant from the mines. The ore as it comes to the mills has received its primary crushing at the mine surface plants in jaw crushers of the Blake type and has been reduced to a run-of-mine size passing a 6 to 10 inch (15 to 25 centimeter) opening. All secondary crushing is done by means of steam stamps.

Milling practice in this district consists of crushing either to 3/16 inch (5 millimeters) or to 5/8 inch (16 millimeters) size by steam stamps, with intermediate reduction by rolls, so that the product for gravity concentration is finer than 3/16 inch (5 millimeters). Separation of the coarser copper is effected by means either of jigs or of shaking tables of the Wilfley type. At all plants fine grinding is done by means of Hardinge or Marcy mills; the extent of this grinding varies at the different plants and depends on the original quality of the rock and the size and distribution of the fine copper.

In all the amygdaloid milling plants of the district flotation has been introduced within the last three years, and all material finer than 35 to 48 mesh (0.73 to 0.53 millimeter) is now treated by that process. Most of these flotation machines are of the Fahrenwald type. The loss of copper in amygdaloid treatment approximates 1½ pounds to the ton (0.67 kilogram to the metric ton), giving a recovery ranging from 90 to 96 per cent of the original copper content of the ore.

The conglomerate ore of the Calumet & Hecla Consolidated Copper Co. is unique in the district as regards both hardness and the quality and distribution of fine copper. Practice on this ore after the customary grinding to 3/16 inch (5 millimeters) in the stamps, preliminary to gravity concentration, consists of fine grinding by means of Hardinge pebble mills, followed by classification and flotation on the slimes (smaller than 200 mesh, or 0.13 millimeter) and by leaching of the sands (larger than 200 mesh). Leaching is done by means of cupric ammonium carbonate solution, the copper being dissolved as cuprous ammonium carbonate, which on distillation yields copper oxide for the smelter, with coincident recovery of the ammonia and carbon dioxide as ammonium carbonate for use in subsequent cycles.

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Developments in metallurgy in the last 15 years have resulted in making valuable the old conglomerate tailings. These are being reclaimed by means of suction dredges and after fine grinding are being treated by flotation and leaching in the same manner as current ore of the same size. This operation has resulted in the recovery in 15 years by the Calumet & Hecla Co. of 268,641,000 pounds (121,853,000 kilograms) of copper at a cost per pound much lower than that of the average mine product.

SMELTING

Smelting, as practiced in the district, is a relatively simple operation. Inasmuch as the copper occurs in the ores as the native metal, the process starts with melting the concentrates in a reverberatory furnace, the gangue being separated as molten slag and the copper recovered in the molten condition. From the melting furnace the practically pure copper is taken to a separate reverberatory furnace, where it is oxidized by air to remove traces of iron and sulphur introduced in melting and is reduced to tough-pitch copper by poling. If the metal is to be used for electrical purposes, the copper from some of the deposits is at this stage treated with soda ash to remove arsenic. Silver is present in too small amounts to make its recovery profitable.

From the refining furnace the metal is cast by mechanical methods into the desired shapes, such as wire bars, cakes, slabs, and ingots. The high purity of the product has always been a point in its favor.

COSTS AND RESERVES

The district as a whole is classed among the high-cost producers, principally because of the low average content of copper in the ore and the great depths from which the material must be mined at many of the properties. The following statement shows the mine production and costs, not including depreciation and depletion, for the year 1929:

Company	Refined copper produced		Cost (cents)	
	Pounds	Kilograms	Per pound	Per kilogram
Calumet & Hecla	90,319,000	41,004,826	11.43	25.17
Isle Royale	10,864,085	4,822,195	14.01	30.85
Mohawk	20,043,127	9,098,570	7.32	16.12
Copper Range	24,197,316	10,985,581	13.26	29.21

In addition to mine production, the Calumet & Hecla Co has a reclamation plant which in 1929 produced 33,511,000 pounds (15,213,994 kilograms) of copper at an average cost of 5.62 cents a pound (12.38 cents a kilogram) from old conglomerate tailings which in early days were discarded. The life of this sand bank is about 12 years.

The future of the going mines mentioned above depends largely upon the selling price of copper and the ability of the operators to find extensions to the ore bodies of suitable grade to replace the reserves now being depleted. Operations in some of the mines have indicated a tendency for the grade of ore to become lower as greater depths are attained. A few properties have been permanently closed on this account, and although this tendency may not apply to all the lodes, the few to which it does not are working at vertical depths of over a mile (1.6 kilometers), where even the most economical methods of mining permit only slight profits. The discovery of new ore bodies is therefore of vital importance to the district.

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ITINERARY

A good view of the Portage Lake district can be had from the top of the hill south of Houghton, near No. 1 shaft, Isle Royale mine. The Isle Royale shafts can be seen close by, and across the valley the Quincy shafts. In the distance toward the south are the Copper Range mines on the Baltic lode. The dumps of the Isle Royale and Baltic lode mines show minerals characteristic of the higher-temperature zones, such as sericite, ankerite, chalcocite, and arsenical copper.

A few miles to the southwest a quarry exposes a good section of traps and amygdaloids and a felsite conglomerate.

One of the sights that tourists usually see is the hoist at No. 2 shaft, Quincy mine, designed to hoist ore from depths as great as 13,000 feet (3,962 meters).

Along the road from Hancock to Calumet are numerous abandoned mining locations, among them the Franklin Jr., Rhode Island, and LaSalle.

In Calumet there are two parallel lines of shafts, of which one serves the Calumet conglomerate ore body, the richest and largest deposit in the district, and the other, about 750 feet (229 meters) in the footwall, serves the Osceola amygdaloid deposit.

It is only a few minutes' ride by automobile from Calumet to the mill and smelter on Torch Lake. The road crosses the Keweenaw fault, which can be seen at Douglass Houghton Falls, reached by a short walk from the highway. This fault is of the reverse type and brings the traps of the copper-bearing series against the younger sandstone on the southeast or footwall side.

Between the Calumet & Hecla smelter on Torch Lake and the villages of Hancock and Houghton the highway passes by the Ahmeek, Tamarack, and Quincy mills. Several interesting outcrops of the Eastern (Cambrian) sandstone can be seen.

Northeast of Calumet the shafts on the Kearsarge amygdaloid are seen on the right. This amygdaloid has been commercially mineralized for a distance of over 5 miles (8 kilometers). It is usually possible to see the typical mineralized rock in the ore hoisted at the Ahmeek shafts. It is of an intermediate zone, showing neither the abundant zeolitic minerals of the cooler zones nor the sericite ankerite of the higher-temperature zones.

One of the felsite bodies that occur in the lower part of the series can be seen southeast of Ahmeek. Some of these felsites are known to be intrusive, but whether this particular one is intrusive or extrusive is not known.

To the northeast along the main highway (United States 41) the shafts of the Mohawk and Seneca mines on the Kearsarge amygdaloid are seen on the right. The cliff rising on the left, which the road follows, is the base of the thickest flow in the district. At the Phoenix mine there is a good view of the base of this flow, with the increasing size of grain showing farther from the contact. An example of the fissure-vein type of the mineralization occurs at the base of the flow.

In the village of Eagle River is a monument to Douglass Houghton, the first State geologist of Michigan. The monument is built up of stone representing the principal rock types of northern Michigan. Below the bridge the Eagle River falls over the

contact between the base of the Great conglomerate and the top of the traps.

The road from Eagle River to Eagle Harbor passes several abandoned mines that prospected or mined the Ashbed amygdaloid and fissure veins intersecting it. The largest of these is the Copper Falls, the dumps of which show minerals characteristic of the lower-temperature zones, such as prehnite, datolite, adularia, and analcite.

At Eagle Harbor are continuous outcrops of the Lake Shore trap, offering opportunities of studying the details of amygdaloid tops. The south shore of the harbor is in the Great conglomerate.

At the Delaware location there are numerous exposures of the Allouez conglomerate, which here carried some copper near the intersections of cross fissures.

From Delaware good roads branch in four directions, one of which leads to Eagle Harbor, already mentioned. Another leads to Copper Harbor and Fort Wilkins, which is of historic interest. Another leads southward to Lac LaBelle, on the north side of which is Mount Bohemia, made up of gabbro that intrudes the traps and conglomerates, and farther on to Bete Gris Bay, from which foot trails and boats may be taken to Mount Houghton, a felsite mass, perhaps intrusive; Bare Hills, a felsite mass known to be intrusive; and other localities, all showing a greater complexity in geology than exists in the productive part of the range. The observer is inclined to wonder at the fact that the outstanding copper deposit, both in size and in richness, is not in these regions showing numerous outcropping intrusives, nor in the faulted and folded areas, but is in the Calumet conglomerate at a place where the structural features are of the simplest kind.

From Delaware to Calumet Highway 41 follows the base of the thickest flow in the district for many miles. Just below this horizon the early fissure-veined deposits, with their spectacular masses of copper, were found. The abandoned locations, one of which, the Central, was a thriving community for 40 years, can now be seen at close intervals.

THE GOGEBIC RANGE

By W. O. Hotchkiss

SURFACE FEATURES

The outstanding topographic features of the Gogebic range are two ridges separated by a valley from 1 to 2 miles (1.6 to 3.2 kilometers) in width. These parallel features extend in a

direction somewhat south of west. Throughout the iron-producing portion of the district from Wakefield, Michigan, to Montreal, Wisconsin, these ridges are broken into isolated hills, owing to cross faults, which have made it possible for the streams to cut their gaps and find their way toward Lake Superior without flowing for any long distances parallel to the valley. To the east and west of this broken central portion other streams flow for considerable distances parallel to the northern ridge before finding a gap which permits them to go through.

The highest altitudes in these two ridges are approximately 1,800 feet (549 meters) above sea level or 1,200 feet (366 meters) above Lake Superior. The higher parts are east and west of the broken central area in which the mines are situated. The streams find their way through the northern ridge at altitudes of 1,300 to 1,400 feet (396 to 427 meters) above sea level and drop the 700 or 800 feet (213 to 244 meters) to Lake Superior within 10 to 15 miles (16 to 24 kilometers). The largest streams find their source only a few miles south of the southern ridge of this district, near the divide between the drainage basins of the St. Lawrence and Mississippi Rivers.

Because of this linear nature of the topography and of the fact that the southern ridge is near the outcrop of a productive iron formation, the roads, railroads, cities, and villages are extended in linear fashion through the central valley.

GEOLOGIC FORMATIONS

The southern ridge is made up of an iron formation, the underlying quartzite, and the Archean granite and greenstone. The northern ridge is made by the lava flows of the Keweenawan series. The valley between the two ridges is underlain by the Tyler graywacke and slate formation. (See fig. 10.)

The rocks of the Gogebic range dip about 60° N. and form the south limb of the Lake Superior syncline. The Keweenawan lava flows and the Keweenawan sandstones conformably overlying them extend continuously from the northeast end of Keweenaw Peninsula into Minnesota.

GEOLOGIC HISTORY

The following brief categoric statement gives the geologic events that produced the Gogebic range according to the present status of our knowledge:

1. The first event was the formation of the Archean rocks, the oldest of the district. Throughout most of the productive portion of the district granite immediately underlies the Huronian rocks. To the east and west greenstones and green schists lie immediately below the Huronian.

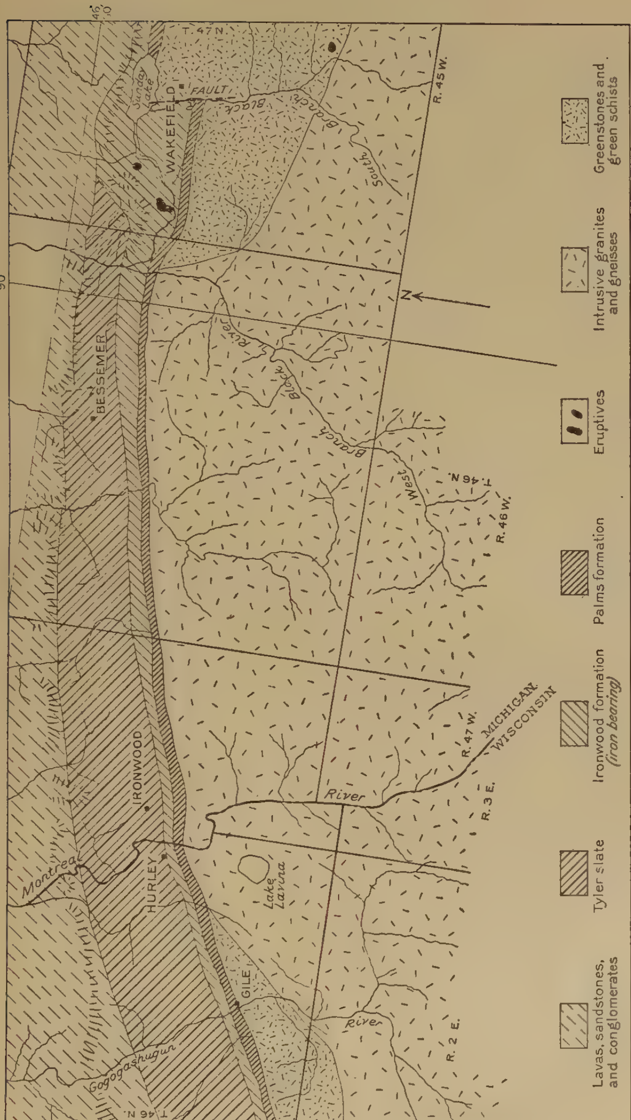

FIGURE 10.—Geologic map of part of Gogebic range. (From U. S. Geol. Survey Mon. 52, pl. 16, 1911)

2. A great period of base-leveling reduced all the rocks to a very even surface.

3. The base-level surface was lowered beneath water level, and the lower Huronian sediments were deposited. These comprise

the Sunday Lake quartzite at the base, which has a maximum thickness of 150 feet (46 meters), and the Bad River dolomite, which has a maximum thickness of about 100 feet (30 meters).

4. The next event was the elevation of the area and the erosion of most of the lower Huronian formations, which occur now only as scattered remnants.

5. The series containing the iron formation was deposited. This is correlated as upper Huronian [3a] by the United States Geological Survey and as middle Huronian by the Michigan Geological survey. This series was introduced by the Palms quartz slate formation, which ranges from 400 to 800 feet (122 to 244 meters) in thickness and is a very fine silty argillaceous rock throughout, with the exception of 30 to 50 feet (9 to 15 meters) of clean quartzite at its top. This is succeeded by the Ironwood formation, which has a thickness of 400 to 1,000 feet (122 to 305 meters). It is described in detail below. Apparently a moderate erosion interval followed the deposition of the Ironwood, and then the Tyler graywacke slate formation was laid down. The Tyler ranges in thickness from 10,000 feet (3,048 meters) down to the vanishing point.

6. Next followed a great erosion interval, in which the Tyler formation and some of the underlying Ironwood formation were eroded. During this period occurred the intrusion of the Presque Isle granite, which is seen in the east end of the range.

7. According to the conclusions of the Michigan Geological Survey, there followed another submergence of the land and the deposition of the Copps formation in the extreme east end of the range, near Lake Gogebic. This formation consists essentially of slate and is highly ferruginous in its western and central parts, with bands of chert and jasper characterizing its lower beds. It is not impossible that the Copps should be correlated with the basal portions of the Tyler formation. (See p. 6.)

8. Another erosion period resulted in base-leveling all the formations exposed.

9. The deposition of the Keweenawan series was introduced by sandstone, now generally altered to quartzite, which has a thickness of 100 feet (30 meters) or more. Upon this were poured out the Keweenawan basic lava flows, a great series having a thickness of nearly 5 miles (8 kilometers). Great intrusions then took place in the Wisconsin portion of the series. The intrusive rocks are mainly gabbro, but large masses of granite porphyry cut the gabbro intrusives.

[3a] This correlation is that given in the monographs. A more recent correlation is given on pages 8 and 9.

10. Tilting, folding, and faulting of the whole series, from the Archean to the uppermost Keweenawan, followed, though some folding and faulting had undoubtedly occurred during the period of volcanic activity.

11. The final major event in the geologic history was the uplifting of this whole series of rocks and the long erosion interval from Cambrian time to the present.

IRONWOOD SECTION

The Palms quartz slate is a fine green silty argillaceous rock. It is thin-bedded and is characterized by ripple marks and minute cross-bedding produced by the ripples. In general it is about 450 feet (137 meters) in thickness, but, like all the other members of this series, it becomes much thicker toward the east end of the productive part of the range and in the vicinity of Sunday Lake reaches about 800 feet (244 meters). Its top is marked by 30 to 50 feet (9 to 15 meters) of clean vitreous quartzite, which makes the footwall for most of the ore bodies.

The Ironwood formation is the economically important member of the series. In it occur all the iron mines and all the iron possibilities of the region. Its metamorphism is described on page 58.

The Ironwood is dominantly a chert formation. Interbedded with the chert are thinner beds of iron minerals. In the unaltered part of the formation the iron minerals are siderite, magnetite, and blue hematite. In the productive part the siderite is entirely oxidized. The thin-bedded portions of the formation, being similar to slates, have often been called slates or, more significantly, ferruginous slates, although the amount of argillaceous material in them is slight. The more dominantly cherty portions of the formation are characterized by irregularly bedded chert in which individual beds may exceptionally attain a thickness of several feet, but beds 3 to 12 inches (7 to 30 centimeters) thick are not uncommon. The formation is divided into five members, named for mines in the district. This division is based upon the character of the material, which is reflected both in the iron content and in the specific gravity.

There are two types of beds—the thin, even bedded and the irregularly bedded. These are shown in Figure 11, which indicates also their distribution in the five members.

The Plymouth member lies immediately upon the top quartzite member of the Palms formation. Its basal portion in places consists of a few feet of quartzite in which the cement is chert, in distinction from the crystalline enlargement of the quartz grains that cement the Palms quartzite. Over this bed in

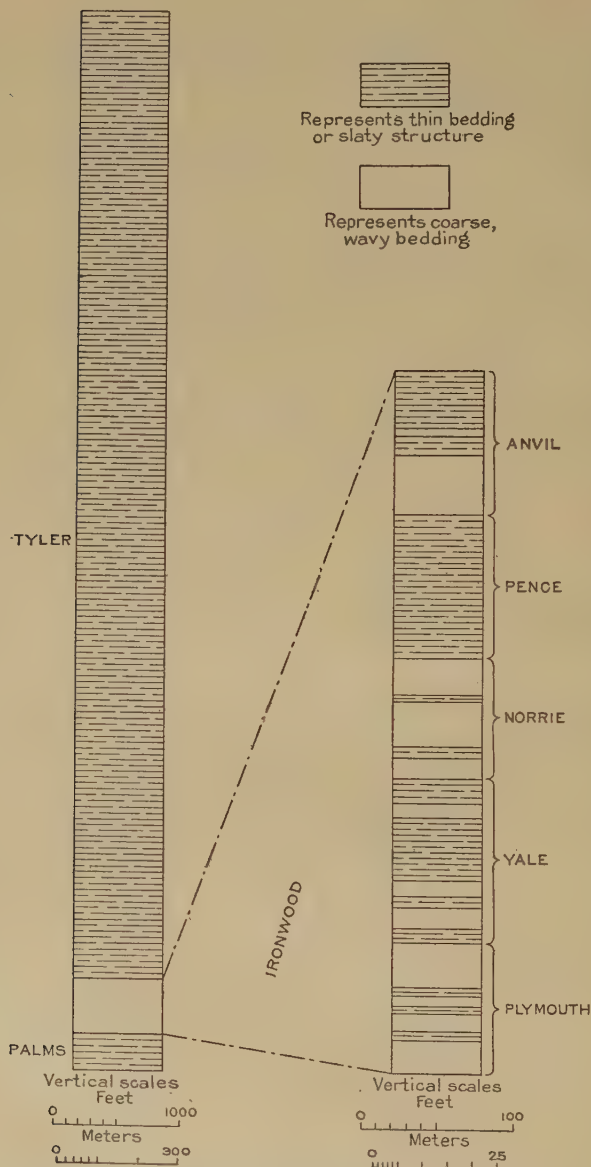

FIGURE 11.—Upper Huronian succession, showing dominance of slaty structure. (From Wisconsin Geol. Survey Bull. 71, fig. 27, 1929)

places is an irregularly conglomeratic laminated and concretionary chert, which is almost undoubtedly of algal origin. This is usually less than 1 foot (0.3 meter) in thickness. Above this is a very thin-bedded ferruginous slate, which is not more than 4 or 5 feet (1.2 to 1.5 meters) thick except at the east end, where the thickness of all the members increases greatly. This bed is known as the "foot slate." Above the foot slate comes the main mass of the Plymouth member, which ranges in total thickness from 100 to 350 feet (30 to 107 meters). It is characterized by the irregular, wavy-bedded chert, with iron minerals occurring both in bands between the chert layers and also as small particles throughout the chert.

The Yale member (see fig. 11) is chiefly of the thin bedded type but contains a number of lesser beds of the wavy-bedded chert type. It ranges in thickness from 65 feet (20 meters) near the west end of the productive areas to 370 feet (113 meters) at the east end. One of the slaty beds is in places highly carbonaceous, and it is this softest member in the whole Ironwood formation which was the horizon of the yielding to a great fault parallel to the beds.

The Norrie member is dominantly a wavy-bedded ferruginous chert that ranges from 30 to 230 feet (9 to 70 meters) in thickness. The thickest portion is at the east end, in accordance with the general rule of thickening of all these formations to the east.

After the deposition of the Norrie member there was a moderate erosion interval, which developed a thin but very persistent conglomerate, composed of pebbles of chert and iron oxide. This conglomerate is known as the "middle conglomerate."

The Pence member is unusually even bedded and throughout most of the range is characterized by the presence of a moderate amount of magnetite. It ranges from 25 to 130 feet (7.6 to 40 meters) in thickness.

The Anvil member is also a wavy-bedded ferruginous chert but differs from the other wavy-bedded cherts in being composed much more largely of rounded chert granules, a small percentage of which shows the ringed structure of true oolites. This member ranges in thickness from 375 feet (114 meters) near Wakefield down to the vanishing point at the west in Wisconsin. In Michigan it has a fairly uniform thickness of over 200 feet (61 meters), but in Wisconsin it is missing entirely except for two thin remnants which appear to be left from the erosion of the rest of the member.

TYLER FORMATION

The Tyler formation lies upon the Ironwood throughout most of the district, except in a few places where it has been removed by erosion. Its maximum thickness is 10,000 feet (3,048 meters). Many of the mine workings that have gone far enough north have disclosed a well-developed conglomerate overlying the Ironwood formation. There is not enough evidence to evaluate satisfactorily the significance of this conglomerate bed, but it is believed to represent a minor erosion interval. This highly ferruginous and conglomeratic lower member of the Tyler has been called the Pabst member. In at least one place it was rich enough in iron oxide to be mined. Associated with the conglomerate are thin beds of dense iron carbonate, which are very pure.

Overlying these beds in the Norrie mine is a bed of black iron carbonate slate. To the west, north of the Montreal and Plummer mines, the lower 150 feet (46 meters) of the Tyler formation is strongly sideritic, containing from 20 to 25 per cent of iron. The next 150 feet contains from 10 to 15 per cent of iron, and the rest of the Tyler contains about 5 per cent of iron, as shown at the drilling at this place. North of this sideritic portion there is also a black slate which is succeeded by the gray slates and coarse graywacke of the main mass of the Tyler formation.

KEWEENAWAN SERIES

The deposition of the Tyler was followed by the formation of the great Sunday Lake fault and an erosion interval of sufficient length to effect the removal of the Tyler and of a part of the Ironwood east of Sunday Lake. Here the initial Keweenawan sediments rest upon the eroded Ironwood in nearly parallel attitude.

The basic lava streams flowed over the first Keweenawan sediments in a direction which is now up the dip. Toward the north the dip of the flows becomes less, so that the topmost flows make a notable angle with the basal flows.

INTRUSIVES IN THE HURONIAN

Numerous basic dikes nearly perpendicular to the beds intrude the iron formation. Two of them are known to intrude both the Ironwood formation and the Keweenawan lava flows, but most of them can not be traced into the Keweenawan.

At Bessemer a thin sill is found near the great bedding fault. This thickens toward the east until it reaches a thickness of 450 feet (137 meters) at the Mikado mine. It is intruded by dikes and is not known to cut any dikes.

At the east end of the series near Lake Gogebic the Huronian formations are intruded by the Presque Isle granite.

STRUCTURE

The Huronian and Keweenawan rocks make a steeply northward-dipping monocline in the Gogebic range. This monocline is the south limb of the Lake Superior syncline, the north limb of which is the Duluth gabbro in Minnesota.

In lesser detail this simple major monocline is complicated by faulting. In the part of the range extending from Mellen, Wisconsin, to Ramsay, Michigan, there are two types of faults—nearly vertical faults perpendicular to the strike and a great fault in the Yale member of the Ironwood parallel to the beds.

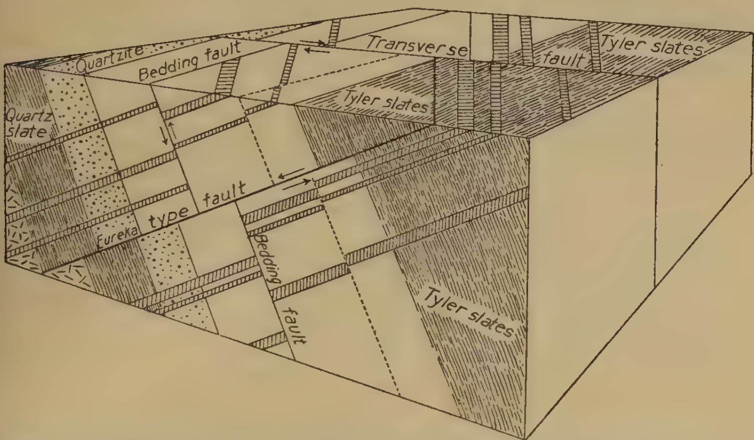

FIGURE 12.—Block diagram showing relation of transverse faults, Eureka fault, and bedding faults in the Gogebic range. (From Eng. and Min. Jour., vol. 108, fig. 21, p. 538, 1919)

The horizontal displacement of the beds due to the vertical faults is rarely as much as 100 feet (30 meters) along the base of the Ironwood. To the north in the lava flows, the horizontal displacement increases greatly and in one locality is known to be 1,500 feet (457 meters). The displacement due to the bedding fault is measurable because of offsetting of the dikes and in some places is about 1,000 feet (305 meters). This fault moved the upper part of the Ironwood to the east.

East of Bessemer occur faults of other types—(*a*) some nearly parallel to the strike and perpendicular to the beds and (*b*) the Sunday Lake thrust. The east end of the range is complexly broken by many faults of all the different kinds and by the vertical cross faults. (See figs. 12, 13.)

The order of development of the structural features of the Huronian and Keweenawan series in this district is apparently as follows:

1. Intrusion of the great sill in the Yale member.
2. Intrusion of the dikes perpendicular to the bedding.
3. Development of the fault parallel to the bedding. This cuts all dikes and the sill.
4. Development of faults parallel to the strike and perpendicular to the bedding, including the Eureka fault in Figure 12. This fault offsets the bedding fault.
5. Sunday Lake thrust fault. This offsets the earlier faults.
6. Erosion of the Tyler formation east of the Sunday Lake thrust.
7. First Keweenawan lava flows, deposited essentially parallel to the bedding of the Huronian, indicating that the Huronian must then have been flat-lying.
8. Tilting of the Huronian and Keweenawan series and development of the vertical faults perpendicular to the strike. These were the last structural events of importance.

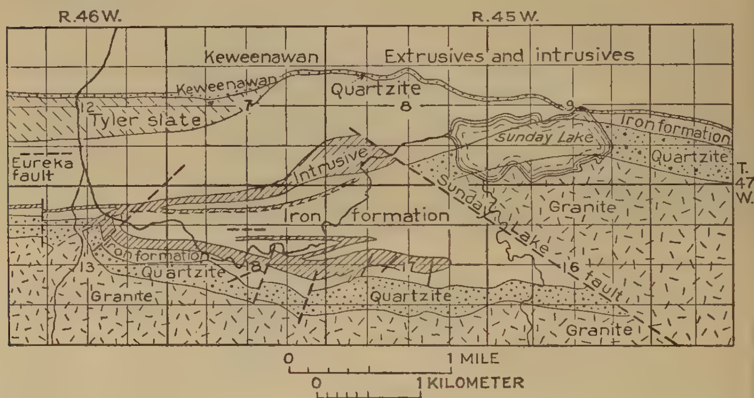

FIGURE 13.—Map of region of Sunday Lake fault. (From Eng. and Min. Jour. vol. 108, fig. 24, p. 539, 1919)

METAMORPHISM

In the west end of the iron range in Wisconsin igneous intrusion has altered the iron minerals in considerable part to coarse-grained magnetite and iron silicate minerals. Farther east the iron formation has been less altered but still shows some development of iron silicate minerals.

From Tylers Fork eastward the iron formation has been subjected only to the metamorphic processes of oxidation and leaching. These are known to have altered the formation to depths greater than 4,000 feet (1,219 meters), but the maximum depth has not yet been shown in mining operations. In some parts of the range the unoxidized and unleached phase of the formation is found at the surface; in other parts it is encoun-

tered only after mining has reached depths of 1,000 feet (305 meters) or more.

The metamorphic effect of the sill and of the dikes in the iron formation is barely noticeable. In a very few places the iron formation shows a baking effect from these intrusives for 2 or 3 inches (5 to 7.6 centimeters) from the contact.

ORE BODIES

All the larger ore bodies are elongated in form and lie in troughs made by pitching dikes and quartzite footwall or by some relatively impervious member of the Ironwood formation. Figures

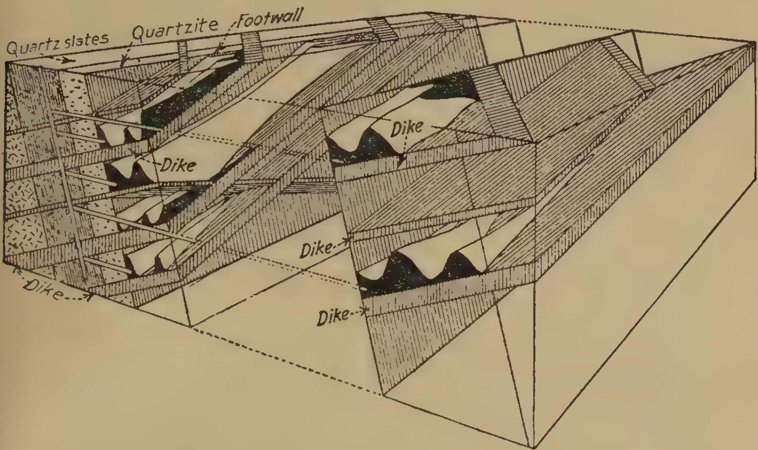

FIGURE 14.—Block diagram showing relation of ore bodies to dikes and the great bedding fault in the Gogebic range. (From Eng. and Min. Jour., vol 108, fig. 26, p. 577, 1919)

14 to 16 show this form and the relations of the ore bodies to the several members of the Ironwood. On the footwall an ore body may rise as a thin blanket for several hundred feet above a dike. The ore is the result of oxidation of the original siderite and of the leaching of the silica, plus a very minor amount of transportation of iron by the leaching waters. In the producing part of the range it is very rare to find any remnant of the siderite until considerable depth is reached, all of the iron formation having been oxidized.

MINING ON THE GOGEBIC RANGE

By Franklin G. Pardee

There was an interval of 35 years between the time when indications of iron were noted on the Gogebic range and the discovery of the first ore at the Colby mine in 1883. The shipment of 1,022 tons in 1884 started the movement of ore from this district. The production increased rapidly, and 11 years later the shipments passed the 2,000,000-ton mark. The largest shipments from the range came in 1920, when 8,763,332 tons

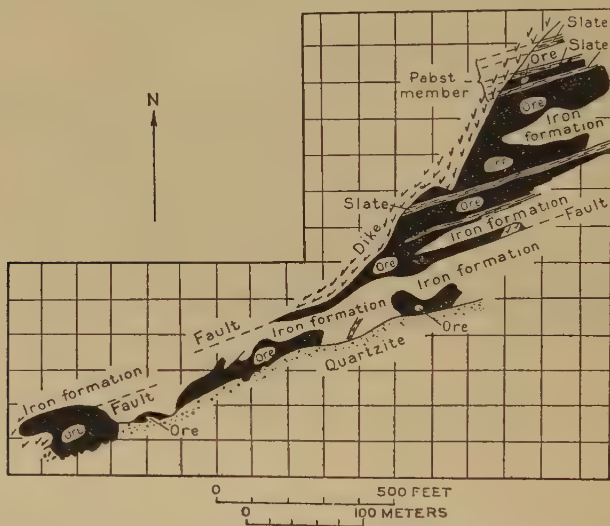

Figure 15.—Plan of an ore body extending almost continuously from footwall to hanging wall in the Pabst mine. (From Eng. and Min. Jour., vol. 108, fig. 31, p. 578, 1919)

was sent out. The total production to January 1, 1931, was 186,325,927 tons, according to the Lake Superior Iron Ore Association.

The three grades of ore produced on the Gogebic range are Bessemer, non-Bessemer, and manganiferous. The manganiferous ore contains only about 4 per cent of manganese and represents about 10 per cent of the total production from the district. There is no hard ore mined on the Gogebic range.

The following analyses show the grade and quality of the ore shipped in 1930:

Average of analyses of iron ores from the Gogebic range for 1930

Grade	Shipments (tons)	Analysis	
		Native iron	Phosphorus
Bessemer	1,042,547	54.54	0.040
Low-phosphorus non-Bessemer (phosphorus 0.18 per cent or less)	3,520,183	52.57	.075
Manganiferous (manganese 2 per cent or more)	450,154	50.51	.070
	5,012,884	52.81	.067

Grade	Analysis			Per cent of total
	Silica	Manganese	Moisture	
Bessemer	7.35	0.37	10.34	20.8
Low-phosphorus non-Bessemer (phosphorus 0.18 per cent or less)	7.40	.63	12.44	70.2
Manganiferous (manganese 2 per cent or more)	7.80	3.84	9.85	9.0
	7.43	.86	11.77	--------

The mining method most commonly employed throughout the Gogebic range is the sublevel caving method. Wherever possible some sort of stoping system is used, but the relatively small number of places in which it can be employed makes this method of little importance. At the east end of the range the ore was found directly under the gravel at a depth that made stripping an economical operation, and two open pits were started. These two operations are really on one ore body and, viewed from the banks, look like one mine.

The details of the mining methods and costs for the Gogebic range are shown very clearly in two circulars published by the United States Bureau of Mines (16, 17).[4]

[4] Numbers in parentheses refer to bibliography, p. 65.

The Gogebic range had in 1931 only two producing mines on the Wisconsin side, the other 15 being in Michigan. The reserves of the ore remaining in the Michigan mines January 1, 1931, were 51,143,511 gross tons. This, of course, does not represent the ultimate recovery that may be expected from the range, because new discoveries will undoubtedly increase the known reserves, as they have in the past. The underground

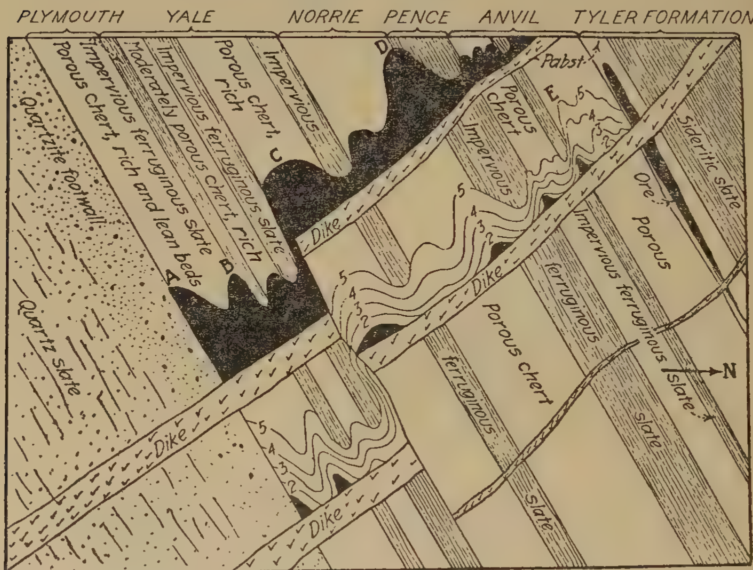

FIGURE 16.—Cross section showing final form (on upper dike) and various earlier stages (on second dike) of an ore body extending from footwall to hanging wall. Width of area shown is about 600 feet (183 meters). (From Eng. and Min. Jour., vol. 108, fig. 32, p. 579, 1919)

mines have reached depths greater than 3,000 feet (914 meters), and as oxidation has been shown to extend down to 4,000 feet (1,219 meters) the final exhaustion of the Gogebic range is many years in the future.

The following tables show the cost of mining on the Gogebic range:

Average costs per ton in underground mines of Gogebic County, Michigan

[From Michigan Geological Survey, Mining statistics for 1930]

	1929		1930		5-year average	
Cost of mining:						
Labor	$0.9687		$1.0372		$1.0768	
Supplies	.5296		.5343		.5090	
		$1.4983		$1.5715		$1.5858
Deferred mining cost		.1192		.1599		.1282
Taxes		.2915		.3285		.3124
General overhead:						
Office, superintendence, insurance, and contingent	.0641		.0696		.0697	
Depreciation	.1312		.1435		.1530	
		.1953		.2131		.2227
Transportation:						
Rail freight	.8204		.8205		.8204	
Boat freight	.8356		.8361		.8355	
Cargo insurance	.0017		.0018		.0017	
		1.6577		1.6584		1,6576
Marketing:						
Selling and operating commissions	.0238		.0257		.0245	
Analysis	.0038		.0033		.0035	
		.0276		.0290		.0280
Total ore cost		3.7896		3.9604		3.9347
Lake Erie value per ton		4.8110		4.8366		4.6545
Gross ore profit [a]		1.0214		.8762		.7198
Other ore costs:						
Royalty		.3583		.4016		.3653
Interest on borrowed money		.0785		.0824		.0791

[a] This figure does not represent true profit, as much ore is sold at a discount.

Summary of statistics for labor, power, and supplies, Eureka-Asteroid mine, 1929

[From U. S. Bur. Mines Information Circ. 6348. Ore mined and hoisted, 401,680 tons. Mining method, sublevel caving]

	Development	Mining (stoping)	Total
Labor (man-hours per ton):			
Breaking (drilling and blasting)	0.259	0.194	0.453
Timbering	.032	.038	.070
Mucking	.039	.179	.218
Haulage and hoisting	.180	.226	.406
General	.084	.105	.189
Supervision	.027	.034	.061
Total labor underground	.621	.776	1.397
Tons per man-shift underground and surface (total labor)			4.43
Tons per man-shift underground			5.71
Labor per cent of total cost			66
Power and supplies:			
Explosives:			
Quantity pounds per ton	0.328	0.382	0.710
Kind and grade	([a])	([b])	
Timber feet b. m. per ton			3.35
Power (kilowatt-hours per ton):			
Air compression			5.63
Hoisting			3.91
Pumping			4.67
Ventilation, lighting, slushing, and haulage			1.41
			15.62
Other supplies in per cent of total supplies and power			35.5
Supplies per cent of total cost			34
Per cent of total cost	20.6	79.4	100.0

[a] 60 per cent gelatin.
[b] 40 per cent gelatin.

Summary of costs per ton, Montreal mine, Nos. 5 and 6 shafts, 1928

[From U. S. Bur. Mines Information Circ. 6369, 1930. Ore hoisted during period, 630,000 tons. Mining method, sublevel overhand open stoping]

	Labor	Supervision	Compressed air, air drills, drill steel	Power
Development:				
In ore	$0.135	$0.009	$0.022	--------
In rock	.078	.009	.055	--------
Mining (including grizzlying)	.138	.017	.010	--------
Transportation	.095	([a])	--------	$0.010
Timbering	.045	([a])	--------	--------
Pumping, ventilation, and miscellaneous accounts	.040	--------	.020	.037
Hoisting	.080	--------	--------	.059
Surface expense chargeable	.052	--------	--------	--------
	.663	.035	.107	.106
Deferred rock development	--------	--------	--------	--------

	Explosives	Timber	Miscellaneous supplies	Total
Development:				
In ore	$0.037	--------	$0.002	$0.205
In rock	.018	--------	.002	.162
Mining (including grizzlying)	.079	--------	.011	.255
Transportation	--------	--------	.015	.120
Timbering	.002	$0.043	.004	.094
Pumping, ventilation, and miscellaneous accounts	--------	--------	.009	.106
Hoisting	--------	--------	.019	.158
Surface expense chargeable	--------	--------	.008	.060
	.136	.043	.070	1.160
Deferred rock development	--------	--------	--------	.06

[a] Supervision included in account of operation.

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GOGEBIC RANGE TO DULUTH

By H. R. Aldrich

The trip from the Gogebic iron range to Duluth bridges the main Lake Superior syncline, and the topography is in general a reflection of the structure. Higher surface altitudes are correlated directly with higher points on the structure and inversely with the stratigraphy. From Mellen to Ashland the route descends over the south limb of the syncline. Ashland lies approximately upon the axis, which strikes N. 45°–60° E. The north limb is complicated by thrusting and downfaulting, and Duluth, though lower topographically, is higher structurally and lower stratigraphically than the upland south of the city of Superior.

Up to altitudes of at least 1,160 feet (354 meters), and hence, in large part, the loose mantle is the deposit of the glacial ancestor of Lake Superior. Here sand and gravel predominate, but in the lowlands clay is dominant.

The region has been subjected to postglacial differential uplift related to an axis somewhere to the south, striking not over 20° north of west or south of east. The amount of tilting has been computed to be between 2 and 3 feet to the mile (38 to 56 centimeters to the kilometer) normal to the axis described, and its effects are observable on the north shore of the lake at least as far as the Canadian boundary.

Mellen, altitude 1,242 feet (379 meters), is just north of Mount Whittlesey, altitude 1,866 feet (569 meters). The city is at the contact between the uppermost of the Huronian formations (Tyler slates) and the lowermost of the Keweenawan (quartzite conglomerate). It is the site of a plexus of faults.

Eastward for at least 25 miles (40 kilometers) the Tyler maintains constant thickness. Westward in 6 miles (9.6 kilometers) it is reduced in thickness from 10,000 feet (3,048 meters) to the vanishing point. The lower Keweenawan conglomerate is continuous eastward. It is not found west of Mellen. The middle Keweenawan (copper-bearing series) normally has an aggregate thickness of more than 25,000 feet (7,620 meters). At Mellen the base of this column of basalts is but a few hundred feet thick. It is succeeded by intrusive gabbro, whose lower contact departs stratigraphically farther and farther from the base of the basalt series eastward, until at the Michigan line, 25 miles (40 kilometers) away, it is 2½ miles (4 kilometers) stratigraphically above the base. Continuing the same trend westward, the gabbro completes its oblique crosscutting of the basalts within a mile (1.6 kilometers) west of Mellen, where it makes contact

with the Tyler slate. The Tyler gradually thins out, and the Ironwood iron-bearing formation becomes exposed in the succeeding 6 miles (9.6 kilometers) to the west, the gabbro coming into contact with the Ironwood formation. The gabbro was apparently injected along a major northward-dipping thrust plane, the western extension of the Keweenawan fault of the Michigan copper district. This thrust and post-Huronian deformation and erosion were the essential factors in the elimination of the Tyler slate west of Mellen.

In the Copper Falls State Park the Bad River, flowing northward through Mellen, crosses the gabbro and swings northeastward across an area bounded by faulting to enter a deep trench controlled by the strike of the basaltic flows, which lie well north of the Keweenawan thrust fault. The stream drops 29 feet (8.8 meters) over basalt ledges and within a short distance is joined by a branch known as Tylers Fork, which drops 31 feet (9.4 meters) immediately above the confluence. The augmented Bad River then flows northward at right angles to the strike through a gorge cut in the Chippewa felsite (?), Outer conglomerate, and Freda sandstone of upper Keweenawan age. These formations stand on edge.

Ashland, at the head of Chaquamegon Bay on Lake Superior, lies close to the principal axis of folding of the Lake Superior syncline.

Immediately west of Ashland glacial-lake beaches are crossed in making the ascent to the summit of the moraine formed between the Chippewa lobe of Wisconsin ice, which occupied Chaquamegon Bay, and the Lake Superior lobe to the west.

The interlobate moraine west of Ashland is dominated by sand with some gravel and boulders and a minimum of clay. It forms the surface of the headland known as Bayfield Peninsula. The core of the moraine consists of middle Keweenawan basalts and upper Keweenawan sandstones, the latter forming bold cliffs at many points along the lake shore and on the Apostle Islands, which lie offshore.

DULUTH ROCKS AND STRUCTURE

By Frank F. Grout

The bluff rising from Lake Superior at Duluth is a remarkably fine exposure of a series of intrusive and extrusive Keweenawan rocks. The program for the examination begins with the underlying formations and lower Keweenawan rocks; is largely devoted to the differentiates of the Duluth gabbro, including their petrography and structure; and ends with the

roof rocks and an overlying thick differentiated sill, probably related to the gabbro.

The oldest formation exposed near Duluth is slate, probably of Huronian age. Scattered outcrops occur for many miles to the west, perhaps as far as the Cuyuna range. Its relations to other formations are not well exposed, except at Duluth, where it is highly folded and eroded and lies unconformably below slightly tilted Keweenawan rocks.

The sedimentary basal Keweenawan is very thin except along the St. Louis River above Fond du Lac (33).[5] A basal conglomerate lies on the slate and in the large exposures grades up into sand, ferruginous conglomerate, and red sandy shale.

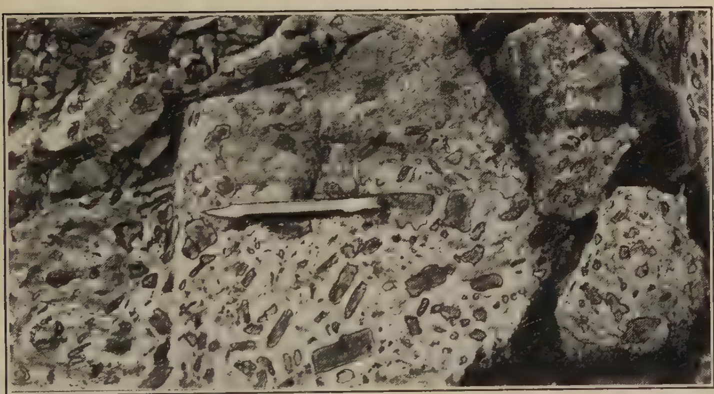
1.[6] North of the exposures in the river bank the basal quartz conglomerate is covered with basalt lava flows, of which seven or more are exposed in the western part of the city, dipping about 10°–15° E. The amygdaloidal zones are of several kinds, distinguished by different minerals—quartz, zeolites, epidote, and chlorite.

After at least eight or ten flows (probably more nearly 100) had built up a considerable thickness of the Keweenawan the Duluth gabbro was intruded into the series and spread into a thick sheet near the base. About the time of intrusion both the roof and the floor sagged down, a movement which gave the intrusive mass the basinlike form named a lopolith (27, p. 518). The petrographic features of this intrusive are noted roughly in the order in which they may be seen in a traverse from the base eastward up into the roof rocks. The structure indicates that at Duluth the intrusive was about 3 miles (4.8 kilometers) thick.

2. The diabase flows a few hundred feet stratigraphically below the gabbro floor are fresh and unaltered except for the amygdules and a little chlorite and serpentine, characteristic of most Keweenawan flows. For perhaps 100 yards (91 meters) the immediate floor rocks are recrystallized into a hornfels (26) and are crossed by gash veins and stringers of gabbro and related pegmatites. The amygdules are recrystallized to feldspars and amphiboles and are so smeared that it seems likely that a considerable mass of the floor was heated until it was of a mushy consistency. The pegmatites that intrude it have also great petrographic variety, ranging from gray gabbro to pink granite even in a single dike. The olivine gabbro pegmatites furnish specimens in which olivine can be seen megascopically without difficulty. There is considerable evidence that these pegmatites

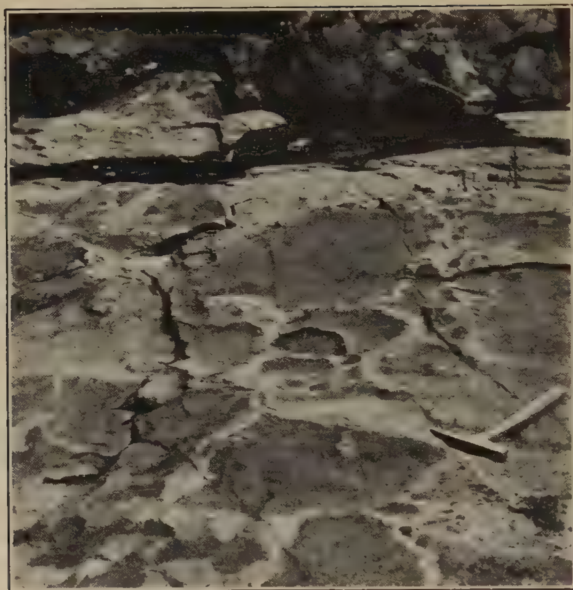
[5] Numbers in parentheses refer to bibliography, pp. 71–72.
[6] Numbers refer to map, fig. 17.

A. DIABASE, ALMOST ANORTHOSITE

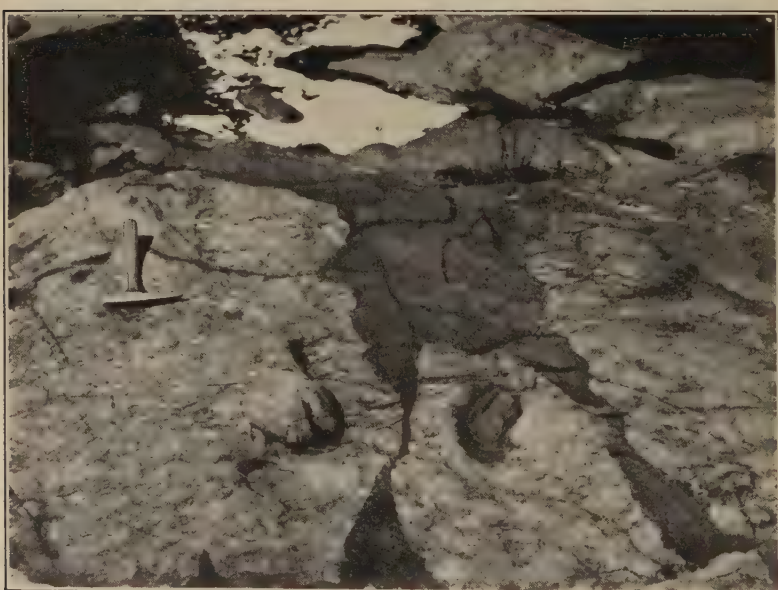


B. PHASE OF RED ROCK (GRANITE) FULL OF ANORTHOSITE FRAGMENTS

The fragments are enough assimilated to make the whole rock gray, like the specimen shown in *A.*



A. HAZY APLITIC RED-ROCK STRINGERS IN THE GABBRO NEAR THE TOP, AT LINCOLN PARK, DULUTH



B. APOPHYSES OF THE MAIN DULUTH GABBRO AT DULUTH

below the main intrusive gabbro formed early, probably before the crystallization of the main magma (28, p. 192).

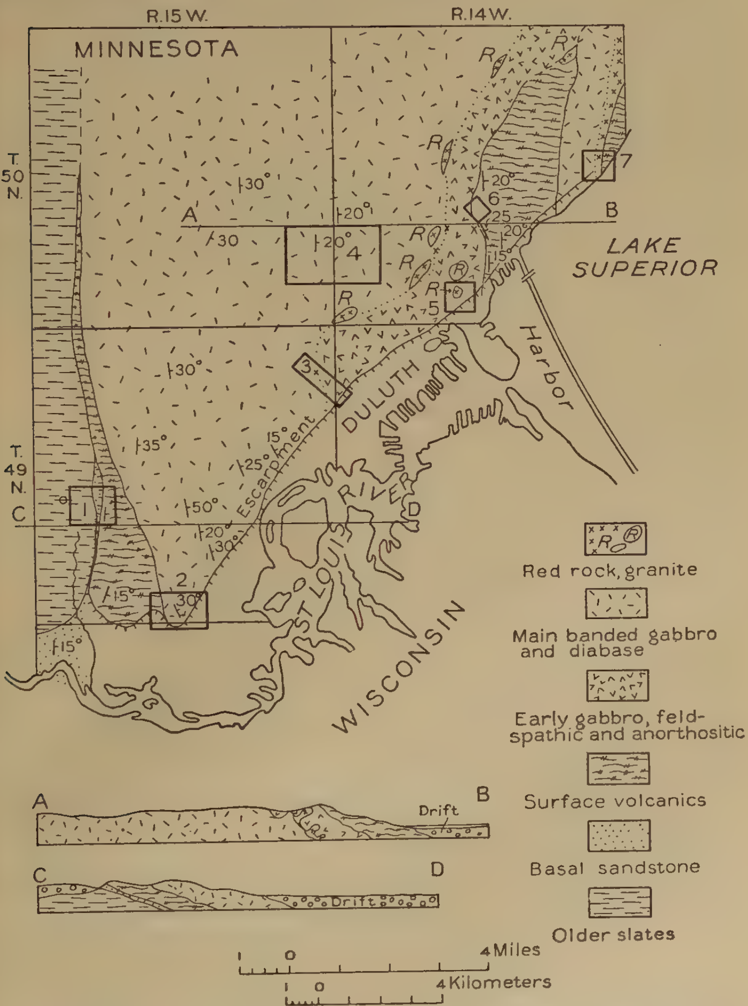


FIGURE 17.—Sketch map and sections of the formations in the vicinity of Duluth. All are Keweenawan except the older slate and the Pleistocene drift. Numbered rectangles indicate localities described in text

Above the floor the gabbro exposures have conspicuous flow layers. (See pl. 5.) Early layers are rich in olivine, but peri-

dotite layers appear only a few hundred meters above the floor. The peridotite is a rather deeply weathered brownish-black friable rock.

The origin of the flow layers, whether by convection during crystallization, by deformation, or by injection of heterogeneous material, or material that became heterogeneous by injection, is a complex problem (21). The evidences of motion include not only the layers of different mineral composition but a parallelism of the needles of feldspar, in the same plane as the layers (29, p. 457). The gabbro with flow layers constitutes the main part of the whole formation, 3 miles (4.8 kilometers) thick, and as the bands range in thickness from half an inch to several feet (1 centimeter to a few meters), there are many thousands of them to be accounted for.

Petrographically the flow layers range from peridotite near the base to anorthosites near the top, with troctolites (olivine-plagioclase rock) and magnetite-rich layers as exceptions in a series chiefly made up of gabbro and olivine gabbro (31, pp. 626–631).

At Duluth the upper phases of the intrusive are somewhat exceptional when the whole area of the intrusive, 150 miles (241 kilometers) long, is considered. In comparison with the main area there is a surprisingly small amount of "red rock," granophyre, or granite; but there is an early feldspathic phase of the gabbro, so early that it somewhat chilled the upper phase of the banded gabbro and its associated red rock. (See pl. 6.)

3. At Lincoln Park (see pl. 7, A) the gradational and aplitic relation of the red rock to the gabbro is very clear, as is also its intrusive relation to the early overlying feldspathic gabbro (31, p. 635). Many red stringers with sharply defined walls can be traced into poorly defined streaks which finally grade imperceptibly into the nearly black gabbro.

4. North of Lincoln Park there are places where blocks of the early gabbro have been stoped into the later gabbro and perhaps partly assimilated. The exposures, however, are not wholly inconsistent with the theory that early feldspar crystals might rise to the upper part of a chamber of gabbro to form anorthosite (32). This might be stoped and intruded by the still liquid magma during the long period of later differentiation to a granitic residual magma. Small flow layers in the main gabbro are true anorthosites, but in the upper feldspathic gabbro large volumes of fairly pure plagioclase rock are exposed (19, 22, 32). It may be significant also that flow layers rich in titaniferous magnetite occur near these outcrops of anorthosite, an association that is known in other districts. The magnetite rocks near

Duluth are very lean and much smaller than those in the gabbro farther northeast (23).

5. At Thirteenth Avenue West a small abandoned quarry shows some very instructive relations between the red granite and the anorthosite. On casual inspection it seems that there is as complete a gradation from red rock to anorthosite here as there is from red rock to gabbro in Lincoln Park. Close study shows, however, that the anorthosite solidified earlier than the red rock, and that the late red-rock phase of the magma shattered and probably assimilated some anorthosite. There is no true gradation from one to the other.

6. Above the anorthosite lie basalt flows, surface breccias of basalt, rhyolites, porphyries, and small amounts of interbedded sediments. One exposure has been found a few miles north of

FIGURE 18.—Exposures of thin lava flows at Duluth Wall, on the north side of East Second Street, between Fourth and Sixth Avenues East

the city, where feldspathic gabbro sends apophyses into its basaltic roof. (See pl. 7, *B*.)

7. At Thirtieth Avenue East there is an exposure of a sill, probably related to the main gabbro, and with a more normal gradation from diabase to overlying granite. The sill is about 1,000 feet (305 meters) thick, but the visible transition from black diabase to red granite occurs in 50 feet (15 meters).

The relations of granite to gabbro are thus shown at Duluth in three situations—(1) in a pegmatite dike in the floor of the main intrusive, (2) in an aplitic phase below an anorthosite near the top of the main intrusive, and (3) in the upper phase of a diabase sill (19, 20, 24, 32).

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THE CUYUNA IRON-ORE DISTRICT

By Carl Zapffe

INTRODUCTION

The Cuyuna iron-ore district, the youngest of the producing districts of the Lake Superior region and the most westerly, is almost devoid of rock outcrops. It is noteworthy because magnetic lines of attraction are important in locating the iron formation and because of its large reserve and large annual production of manganiferous iron ores.

The ore-bearing rocks of this district and an extensive area surrounding it have a lithology and geologic structure which distinguish them as part of the uppermost group of the Huronian series in central Minnesota. The limits of the upper Huronian are still unknown, because of concealment by glacial drift. Rock outcrops being lacking, the presence of the ore formations has invariably been indicated in advance of drilling by lines of magnetic attraction. Such lines are numerous and may be found in eight counties. Explorations have been made preponderantly in Crow Wing County, and only in this county has sufficient ore been found to justify mine development. More

than 6,000 drill holes have been put down, and the mines started number 42.

The magnetic belts in the Cuyuna area are shown in Figure 19. The belts in Crow Wing County occupy two major areas, known as the North Range and South Range. Mining has been conducted in both areas, but at present ore production is confined

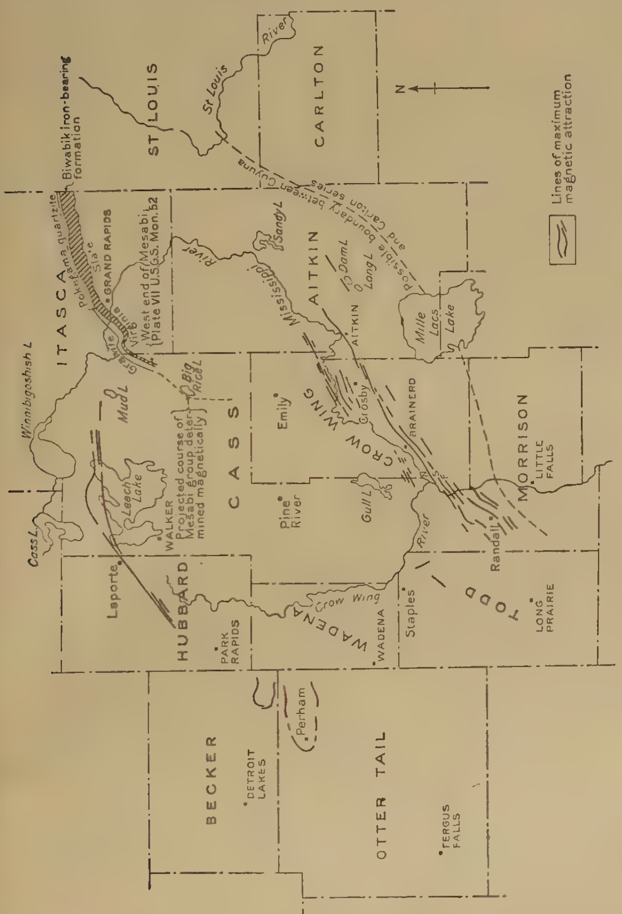

FIGURE 19.—Map of east-central Minnesota showing magnetic areas in the Cuyuna district and their relation to the west end of the Mesabi range

to that part of the North Range which lies southeast of the Mississippi River, an elliptical area 6 miles (9.6 kilometers) wide and 8 miles (12.8 kilometers) long.

There are no outcrops in the productive part of the Cuyuna district. On the south and on the extreme western borders

seven outcrops occur, all of them very small and far apart and consisting of different rock types—namely, a dark-green schistose sediment, a slaty amphibole magnetite, a basic porphyritic intrusive, a gabbro intrusive, an epidote granite, a schistose diorite, and a quartzite. On Figure 19 is shown a line suggesting a southeast boundary for the Cuyuna area; to the south and east of this line are extensive areas of graywacke, micaceous schists, hornblende schists, garnetiferous and staurolitic schists, and acidic and basic intrusives. To the north the nearest outcrops are those of the Mesabi district, 60 miles (97 kilometers) distant.

The glacial drift that covers the ore-bearing area ranges in depth from 25 to 200 feet (7.6 to 61 meters), but most of it is about 100 feet (30 meters) deep. In the outlying areas it is 200 feet or more deep. The area is fairly flat but is accentuated here and there by moraines.

The small quartzite outcrop at Dam Lake, in the south-central part of Aitkin County, was originally supposed to be at the base of an iron formation, like the similar rock in the Mesabi district. On this premise the Cuyuna district was prognosticated, and drilling was begun in 1903. No ore formation was found at this place, but the first hole drilled 20 miles (32 kilometers) to the west, on a magnetic belt in Crow Wing County, encountered ore formation but no quartzite. This idea of the continuity of a quartzite and a succession of rock formations similar to that of the Mesabi district influenced explorers and dominated geologic interpretations for many years, even though all disclosures meanwhile were in discord with such views.

The statements made below regarding the geology of the Cuyuna district express the opinion that the ore formations of the district are of upper Huronian age and younger than the ore formation of the Mesabi district, which is now considered to be middle Huronian.

GEOLOGIC FORMATIONS

The rocks of the Cuyuna district have been divided as follows (40) (see also pp. 8–9):[9]

Post-Keweenawan: Shaly sediments and conglomerates.
Keweenawan:
- Basic intrusives and extrusives.
- Acidic intrusives.

Upper Huronian:
- Crow Wing formation—
  - Cuyuna member. Mainly green slaty and schistose rocks (partly volcanic), inclosing the Deerwood iron-bearing member. Strongly magnetic.

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[9] Numbers in parentheses refer to bibliography, pp. 87–88.

Upper Huronian—Continued.
 Crow Wing formation—Continued.
  Emily member. Some green but largely dark-colored slaty rocks, probably few if any volcanic rocks, and many scattering lenses of iron-bearing rocks, which only are slightly magnetic or nonmagnetic.
 Aitkin formation: Gray slates and phyllites. Volcanic rocks absent. Contains some iron carbonate, but extensive iron-bearing lenses are virtually lacking. Nonmagnetic.
 Basal conglomerate.
Middle Huronian.

Basal conglomerate.—Two drill holes in the southwestern part of Itasca County and in Cass County showed 10 to 12 feet (3 to 3.6 meters) of firmly cemented conglomerate of quartzite and particles of iron formation lying on banded Virginia slate; another hole showed the conglomerate resting on the Biwabik iron-bearing formation.

Above one of these conglomerates and under glacial drift was found 50 feet (15 meters) of light-gray shale containing small flakes of sericitic minerals. Similar material 200 feet (61 meters) thick, under a deep surface mantle, was also found lying on granite and Keewatin greenstone. In five other drill holes nearly twice this thickness of the same rock was cut above the Virginia slate south of the iron-bearing formation. When these five holes were drilled it was not possible to make observations for conglomerate. At no other place has drilling reached this basal layer of conglomerate.

Aitkin formation.—The light-gray material mentioned above is also disclosed in Aitkin County, 8 miles (12.8 kilometers) to the southeast. Here also it is under glacial drift and grades downward into gray slates and phyllites obtained as drill cores. These slates and phyllites underlie a large area in the northern and eastern parts of Aitkin County and extend into the northeast corner of Crow Wing County and presumably into the southeastern part of Cass County. This whole area is notably lacking in green rocks, either of sedimentary or of volcanic origin, is without magnetic attractions, and contains no ore deposits.

A few narrow lenses of unoxidized iron carbonate have been encountered in Aitkin County. They are white, contain abundant rounded grains of detrital quartz, and show on analysis about 20 per cent of iron and 1 to 6 per cent of manganese. The manganese content increases toward the basal portion of the lenses, just as it does in the iron-bearing lenses to the southwest, in the productive part of the Cuyuna district. Similar lenses of unoxidized iron carbonate have been found in several other places occurring higher in the Cuyuna section.

Here and there thin bands of ferruginous slate have been found, but nowhere has anything been encountered that would

be called an ore deposit or that would even be deemed sufficiently encouraging to warrant following it closely in the hope of finding an ore deposit.

Crow Wing formation.—Nothing has been disclosed which suggests that the Aitkin and Crow Wing formations are unconformable. The differences between them are principally lithologic and suggest gradation. In the lower part of the Crow Wing formation black and graphitic slates become abundant, and gray slates and phyllites, characteristic of the Aitkin formation, are uncommon. Green slates and green schistose rocks are more and more abundant toward the upper part of the Emily member, the lower division of the Crow Wing. Iron-bearing lenses in the Emily member are numerous but appear to be scattered and short. Although some are but little oxidized, most of them are heavily oxidized, and one, near Emily village, is almost rich enough in iron and manganese to constitute an ore deposit. Manganese is not uncommon. Magnetic lines are numerous but generally are weak and short.

Because of folding, the Emily member is distributed along the western border of the Aitkin formation and can be traced in semicircular fashion through the middle-western part of Aitkin County, trending northwest through the northeast part of Crow Wing County and into Cass County, or southwest toward Mille Lacs Lake. (See fig. 20.)

Toward the upper part of the Emily member the green rocks become dominant over the darker rocks, and gradually all the differences become sufficiently pronounced to justify considering the upper part of the Crow Wing formation a separate member, now named the Cuyuna member. The Cuyuna member contains an abundance of volcanic rocks, consisting of the basic flows and layers of tuff, which are very schistose and green and are commonly called "green schist." It also contains inconspicuous small, thin layers of dark sedimentary rocks and in addition nearly all the beds of quartzite that drilling has disclosed, the only horizon markers in the member. These beds are not basal selvages.

The Cuyuna member contains the productive beds of the Cuyuna district. Near the base of the member is a persistent layer of ore formation, and about 500 feet (152 meters) or more above it is a second layer; collectively these are called the Deerwood ore-bearing member. It is believed (53) that the Deerwood member consists of two major bands, and that the portion in the northern part of the North Range (T. 47 N., R. 29 W.) is the lower band, of which the South Range band is the probable extension or equivalent, and the portion in the southern part of the North Range (T. 46 N., R. 29 W.) is the upper band.

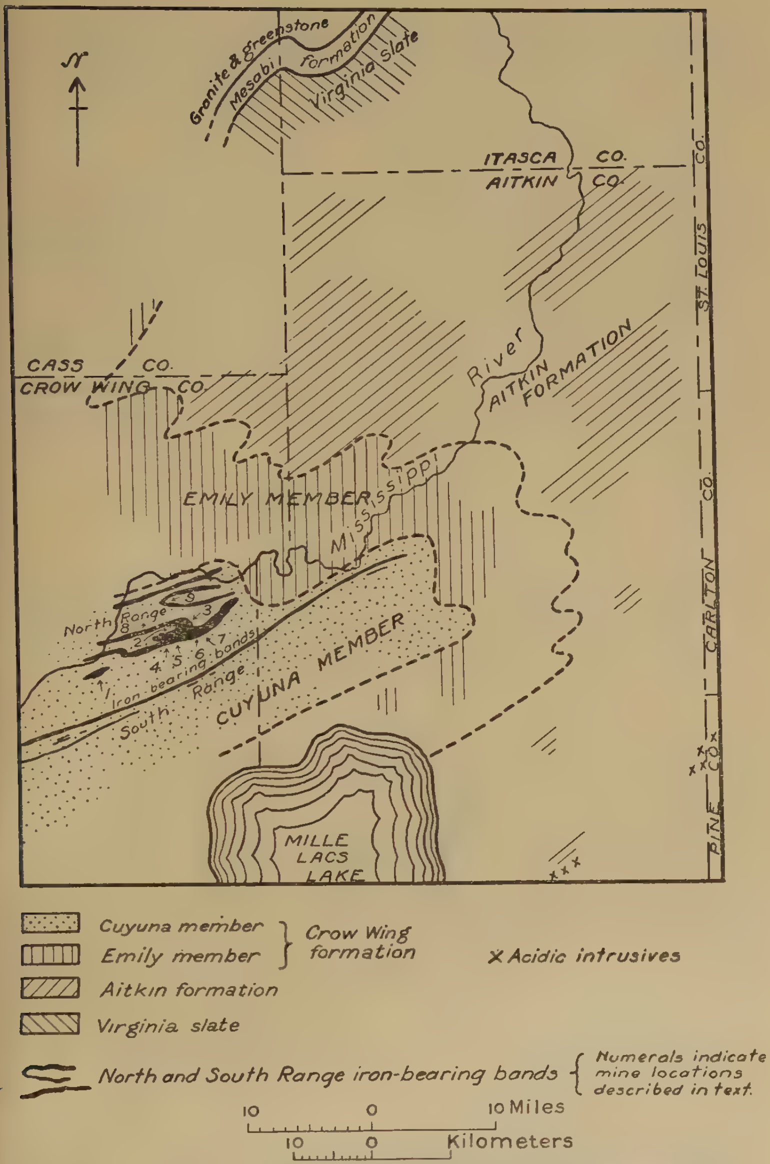

FIGURE 20.—Map showing probable boundaries between the geologic subdivisions in the Cuyuna district

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(See fig. 21.) Characteristically, where much manganese is present it occurs principally in the lower parts of these bands. Most bands are strongly magnetic. The lower band of ore formation in many respects also carries out the idea of a gradation from the poorer bands of the Emily member to the better (upper) bands of the Deerwood. Adjacent rock formations support this view.

The upper band of iron formation is now restricted to a relatively small area. It marks a syncline—to the east the upper band pitches upward and is eroded; to the west it pitches downward and is buried. Throughout the Crow Wing formation variability of sedimentation is a dominant feature.

Keweenawan series.—Only in the South Range have basic effusive rocks been found on the top of the present surface of the Huronian rocks, and they are not extensive. These basic effusives seem to occupy small depressions, a condition which sug-

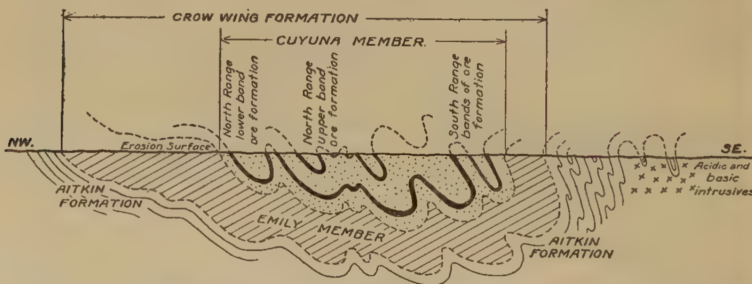

FIGURE 21.—Diagrammatic cross section of the Cuyuna district. The horizontal distance indicated is about 60 miles (96 kilometers)

gests that they are protected erosion remnants of larger flows. They are light to dark green, rather fine grained, and amygdaloidal. Dark basic intrusions are also far more common in the South Range than in the North Range; farther south, in Aitkin County, subsilicic rocks and granites crop out. Still farther south acidic intrusives are abundant, some of which are probably lower Huronian and some perhaps Archean.

Post-Keweenawan rocks.—In one part of the South Range, in an area a little over a mile (1.6 kilometers) in length, are horizontal beds of soft gray, green, and reddish shaly material, containing conglomerate at the base or above the base. The complete distribution of this material has never been determined, but it is undoubtedly far more extensive than drilling has disclosed. In their main part these beds are 100 to 120 feet (30 to 37 meters) thick, but they grade down to a thin veneer. These flat beds rest with pronounced unconformity on steeply

dipping beds of the Cuyuna member. They appear to be erosion remnants, but the largest patch has an irregular top surface and if the overlying glacial drifts were removed would be seen as a mound.

STRUCTURE

The Crow Wing and Aitkin formations appear to form a huge synclinorium pitching to the southwest. (See fig. 21.) To the northeast is exposed the base, or Aitkin formation; encircling it to the west and south is the Emily member, and west of that the Cuyuna member. Anticlines and synclines of higher orders parallel one another and by giving rise to projections and embayments of the one member into the area occupied by the other yield sinuous boundary lines. (See fig. 20.)

To the northwest folding has been less intense and the sediments are less metamorphosed. To the south and southeast, in Aitkin County, igneous intrusions are abundant and folding has been intense, perhaps because of the intrusions. Here the sediments have been strongly metamorphosed, in great contrast with those far to the north.

The lines of magnetic attraction that are easy to follow are almost entirely in the uppermost member (the Cuyuna). The magnetic lines are best developed over great lengths in the South Range. These extend into the western part of Aitkin County but end 6 miles (9.6 kilometers) northeast of Aitkin village. In Aitkin County drilling shows more and more of the Emily type of rocks nearer and nearer to the main magnetic line. The Cuyuna member presumably pinches out near Aitkin village, because of a southwestward-pitching syncline. Near the end of this magnetic area the Emily member swings around it toward the south, but farther east the Aikin formation is reached. The magnetic lines and the good iron-bearing formation stop with the ending of the Cuyuna member.

In like manner a traverse northward from the most northerly line of magnetic attraction in the Cuyuna member, in the North Range area, Crow Wing County, would cross the beds and go downward geologically into the Emily member. Parallel magnetic lines are found there, but they exhibit different characteristics. Wherever one goes from the Cuyuna to the Emily member the magnetic lines become indistinct and less reliable as a guide to ore formation.

In this small area the Emily member covers a width at the surface of 8 to 10 miles (12.8 to 16 kilometers). The Aitkin formation, which in general direction lies to the northeast, occupies an area of 30 or more townships, an extent which undoubtedly predicates a very great thickness, even after allowance

is made for the intricate folding. To the southwest of the Emily lies the Cuyuna member, which occupies a very large area but which is probably not as thick as the Aitkin formation.

ORE DEPOSITS

An explanation of the occurrence of large quantities of iron ore with a high content of manganese calls for close scrutiny of many facts. If the known ore-bearing bands are restored to horizontal positions, it becomes evident that they represent a vertical succession of beds separated by varying thicknesses of barren and preponderantly green rocks. It then also becomes apparent that the manganese is preponderantly in the lower portion of each thickness of formation, although not uniformly distributed through the whole length or the total thickness of the beds. Folding has given rise to a distribution of these manganiferous beds which creates confusion, because, as a result, the manganiferous ores in the several deposits of the district are now found in all positions with respect to footwall or hanging wall and central portions, modified further by the height and pitch of the uplift and the depth of erosion.

In some places manganese was taken into solution subsequent to the uplift and redeposited in joint planes in originally nonmanganiferous iron-ore beds. Deposits formed by replacement along joint planes are conspicuous, but such deposits do not contain a high manganese content.

The original source of the iron and manganese metals is ascribed to surface waters, which took the metals into solution from the rocks occupying the land areas over which they flowed. Recent investigations by the writer suggest the adequacy of such source, and the sequence of manganese forming the basal layers and of iron forming the upper layers is orderly and natural. The accumulation of much manganese is merely dependent on suitable conditions for its precipitation.

Secondary concentration through the circulation of cold meteoric waters, after folding and during the period of erosion, followed here as in other Lake Superior districts and has given rise to commercially valuable deposits extending downward from the rock surface.

The bands of ore formation dip preponderantly at 60° to 90°, more commonly to the southeast than to the northwest. In one small area about 1 mile (1.6 kilometers) wide and 2 miles (3.2 kilometers) long, in T. 46 N., R. 29 W., in the North Range, doming has raised the bottom of the syncline, and flat dips occur in many places, but even here small folds showing steep dips are numerous.

Where simple monoclinal structure is present, the ore deposits take the form of long, narrow lenses. Elsewhere they have a large variety of shapes, because concentration has been distinctly governed by the presence of troughs and crests of local folds.

The ore bodies are generally less than 400 feet (122 meters) thick. Where folding has flattened the formation, or where it has duplicated the beds, greater widths of ore occur. On the other hand, many lenses of ore are only 40 to 100 feet (12 to 30 meters) wide. These widths have determined shaft or pit mining.

Extensive tests for depth have not been made in drilling. Ore has been encountered down to 1,020 feet (311 meters). In 1931 the deepest mining was at 480 feet (146 meters), but plans had been made to sink to at least 630 feet (192 meters). The ores are the highly oxidized parts believed to be due to the downward circulation of meteoric waters. Consequently they are of many shapes and variable dimensions.

So far no evidence has been disclosed which would warrant the conclusion that igneous intrusives have had any influence in localizing an ore deposit. In many places the iron formation has igneous rocks as wall rocks, but these are contemporaneous interbedded tuffs and flows, now very schistose and in advanced stages of alteration.

ORES

The Cuyuna district produces low-phosphorus and high-phosphorus non-Bessemer ores but is unique because of its preponderance of manganiferous iron ores. In recording the production of Lake Superior ores for annual statistics it is customary to designate as manganiferous iron ore any ore shipped containing more than 2 per cent of manganese. Ores of that grade are judged, however, by their combined metallic content, and 45 to 46 per cent in the natural or undried state is the lower limit. The Cuyuna district has not only a larger reserve of such ores than other ranges but it produces more than half the tonnage required annually; its ores have also a higher manganese content, and some mines are operated to produce only ore of that class.

In the Cuyuna district manganese is rarely under 5 per cent. Prior to 1917 shippers strove to obtain an average content of 10 per cent or more and to supply grades as each consumer desired. In recent years the ores have been mixed to yield substantially a 6 per cent and an 8 per cent grade. The total output for the years 1929 and 1930 averaged as follows:

Year	Ore shipped (tons)	Iron (natural)	Phosphorus	Silica	Manganese	Moisture
1929	1,174,309	37.20	0.264	8.95	8.57	14.60
1930	1,007,477	39.71	.263	9.09	7.98	12.72

These outputs came from the high-moisture ores, which are lower in manganese and silica but have been cheaper to mine.

Cuyuna ores are preponderantly high-phosphorus ores, of limonitic character, but the North Range ores differ from other ores of that classification in that they contain only 0.250 per cent of phosphorus, whereas those of other districts contain between 0.350 and 0.450 per cent. South Range ores average over 0.400 per cent, and those of the western part are higher than those of the eastern part. The average analyses of the high-phosphorus ores shipped in 1929 and 1930 are as follows:

Year	Ore shipped (tons)	Iron (natural)	Phosphorus	Silica	Manganese	Moisture
1929	760,540	51.91	0.246	8.90	0.97	8.75
1930	535,825	52.87	.252	8.83	.92	7.87

A few mines contain some low-phosphorus ore, and one mine produces it exclusively. It is hematite and is very fine grained and sticky when the least bit wet. The average analyses for 1929 and 1930 are as follows:

Year	Ore shipped (tons)	Iron (natural)	Phosphorus	Silica	Manganese	Moisture
1929	503,291	51.36	0.098	11.18	0.42	9.96
1930	176,172	53.24	.078	11.28	.23	10.09

The high content of silica is noteworthy. It is a peculiarity of all North Range ores that regardless of classification they may be grouped into low-phosphorus high-silica and high-phosphorus low silica ores. The reason for such relations has never been studied. The relation has long been known for the manganiferous ores, which have been described in detail by the writer (37). In the manganiferous ores the low-phosphorus ore is called black ore, and in the iron ores it could be similarly designated as red. The high-phosphorus ores of both classes are always brown. Just as the red iron ores are higher in iron than the brown ores,

so the black manganiferous ores are higher in manganese than the corresponding brown ores. It does not follow that the higher the silica the higher the content of metal, because beyond a certain point a further increase of metal content is accompanied by a decrease in silica.

The black manganese ores containing 15 to 22 per cent of manganese were mined only during the war period. They are confined to the lower part of the iron formation. Some black ore is found in the upper band, interbedded with brown ores, but these black ores have mineralogic features that distinguish them from those of the lower horizon.

Where manganiferous ores occur in abundance, the manganiferous bed forms the basal layer. In deposits occurring in folded beds manganiferous ore may obviously be found on one or both walls or in the middle, but the statement made constitutes a guide for establishing the location of the basal layer. Only rarely is a small and isolated lens of manganiferous ore found at a higher horizon.

A complication arises as a result of the fact that since the deposit was formed manganese has been redissolved, has migrated, and has replaced iron ore. It can be observed along joint faces of blocks of ore, but an analysis of the ore only would be misleading.

On the South Range a single bed is repeated, and the unoxidized ore formation is everywhere a banded, slaty amphibole magnetite containing an abundance of iron carbonate. The ore deposits are at the rock surface and are deemed oxidized phases of this rock and show all its characteristics. The South Range is not fully explored, but so far no deposits of manganiferous ore have been disclosed there.

On the North Range there are two bands of the ore formation. The lower one contains an abundance of amphibole magnetite in some places, but this band is also highly manganiferous in other places. Except for the latter fact, those ores and the South Range ore have much in common. The upper band shows amphibole-magnetite slates in numerous places at the surface, but in some places all evidence of such a rock is lacking, and coarsely bedded ferruginous cherts and finely bedded hematitic slates constitute the whole mass. The ores developed from them show the characteristics of those two types of rock.

That the manganese layer is basal is in conformity with data obtained by the writer in recent experiments with the removal of manganese from surface and ground waters. It is a natural consequence under certain existing physical conditions, and therefore this occurrence offers nothing that is the consequence of rare conditions other than that manganese was present orig-

inally in the sea. It could then be deposited as an oxide as well as a carbonate; the carbonate would be oxidized later upon exposure to meteoric circulation.

PRODUCTION

The district has been shipping ore every year since 1911. At the end of 1930 the total output was 31,726,756 tons. The annual output is now about 2,000,000 tons. The maximum shipment was 2,596,186 tons. In 1922 the production of manganiferous grades was 43 per cent of the total output, and since 1924 it has been over 50 per cent; in 1925 it was 62 per cent.

The mines are both shaft and open-pit mines. Of late years pit mining has predominated and with it has come an increased output. The greatest number of producers was 29, in 1918. Since 1922 production has come from 12 to 17 properties; but there has been a progressive consolidation of operators, and in late years only about 10 companies have been producing. Even some of these are so closely related to one another that only five mining organizations are now engaged in the district.

Estimates of reserves have varied, mainly because of changes in the application of ores of different types. The only public record of reserve tonnage is that of the Minnesota Tax Commission. The 1930 estimate is 66,095,144 tons of all classes of ore, the greatest total ever recorded. Much work is being done in devising methods of beneficiation, especially in regard to manganiferous material, and eventually the tonnage of Cuyuna reserves will be greater than the figure above given. In the earlier years Cuyuna properties were not drilled to disclose manganiferous ore, but, strange as it may seem, drilling was directed to avoid it. There was then no market for such ores, and abundance of manganiferous material was a nuisance to explorers. It has been shown (38) that the Cuyuna district can safely be counted on to deliver eventually 44,000,000 tons of manganiferous ores. The mines operating at present have more than enough such ores to meet current demands for many years.

TYPICAL MINES

The following notes briefly describe some typical mines of the Cuyuna district which show the different types of ores characterizing the district and the processes of beneficiation used. The numbers refer to corresponding numbers on Figure 20 showing the location of the mines.

(1) *Sagamore mine* (drying; brown manganiferous ore).—This mine has the largest deposit of manganiferous iron ore in the

district. The total shipments are over 2,000,000 tons. In its natural state some of this ore has a moisture content as high as 20 per cent. The ore is heated in rotary kilns and the moisture reduced to about 13 per cent. This is the largest drying plant in the Lake Superior region. As shipped, this ore contains 36 per cent of iron and 8 per cent of manganese (natural). The ores occur in two intersecting shallow synclines isolated from other bands of formation. The maximum length of the deposit is three-quarters of a mile (1.2 kilometers).

(2) *Mahnomen and Louise mines* (crushing; brown manganiferous ore).—An observer standing at the south edge of the stripped area of the Mahnomen and Louise mines sees three pits. To the left is the new Mahnomen, to the right the old Mahnomen, and in the center the Louise. The new Mahnomen and Louise deposits are continuous on the same band of formation, here depressed into a narrow syncline in the middle of the major syncline. East of the Louise is the Hopkins-Sultana deposit, in a parallel syncline, and west of the new Mahnomen is the Alstead pit, all on the same band of iron formation but not marking a continuous deposit of ore. The old Mahnomen is also a synclinal deposit but is south of and parallels the new Mahnomen. The Alstead and Louise are operated by one company, and the Hopkins-Sultana and the two Mahnomen pits by another company. The operator of the Louise pit has also a shaft operation on the same property; it is north of the pit, and the deposit is located on the crest and south limb of an anticline. The production from this group is preponderantly brown manganiferous ore. Each operator mixes the product from his several mines and obtains thorough mixing and uniformity of grades by running his ores through a crushing plant. The Mahnomen crushing plant is a typical installation for handling Cuyuna ores. The Mahnomen ore contains 6.50 per cent of manganese (natural). The Louise mine produces three grades—one with 5.50 per cent, one with 7.50 per cent, and one with 9 per cent of manganese (natural). The higher content is the result of including black ores produced in small amounts from the shaft operation. The Louise-Alstead group has produced about 2,500,000 tons, and the Mahnomen-Sultana group over 4,000,000 tons. Each operator produces about 300,000 tons a year.

(3) *Hopkins-Sultana and Alstead.*—Referred to under No. 2. The former affords a view from the east end, and the latter a view from the west end.

(4) *Feigh* (reddish-brown iron ore).—An underground mine, idle in 1931. The known depth of ore is 750 feet (229 meters); the greatest width, 250 feet (76 meters); reserves, 5,000,000 tons. The structure has many local irregularities but is essen-

tially monoclinal, with southeast dip, forming the south limb of the major syncline of the upper band of ore formation. Westward the continuation of the Feigh deposit is known as the Hillcrest mine, making an over-all length of 1 mile (1.6 kilometers). This deposit consists of nonmanganiferous ore. None of the ore is treated. It is reddish brown and rubbly and as produced contains 50 per cent of iron (natural), 0.265 per cent of phosphorus, and 8 to 10 per cent of silica. This deposit has some of the reddish low-phosphorus high-silica ore, which is more abundant farther east.

(5) *Armour Nos. 1 and 2* (several classes of ore).—These are two underground mines, operated by the same company. Workings are still above the 400-foot (122-meter) level. The deposit in Armour No. 1 consists of two narrow bands of ore of great depth on the limbs of a closely pressed syncline dipping southeast. No. 2, lying east of No. 1, is partly on the same syncline and partly on a series of minor folds to the south resulting from uplift of the trough of the major syncline. Armour No. 1 has produced over 2,000,000 tons and yields about 35,000 tons annually; the ores are brown manganiferous and brown high-phosphorus ores. Armour No. 2 has produced 4,500,000 tons, and the annual output is about 200,000 tons; the ores are mainly the soft red low-phosphorus iron ores, but a considerable tonnage is brown manganiferous ore, and a little is high-phosphorus ore. These ores are not treated in any manner at the mines but are mixed as desired at the coal dock. The total reserves approximate 5,000,000 tons.

(6) *Evergreen, Wearne, and Portsmouth mines* (sintering; limonitic ores).—These three properties are operated as one pit by the Evergreen mine operator, who owns and operates the sintering plant. This mine is three-fourths mile (1.2 kilometers) in length, but the ores in the several properties occur as offsetting lenses situated on crests and in troughs of closely spaced parallel folds, which produce considerable width, length, and irregularity in distribution of several classes of ores. These ores are brown manganiferous ores and brown iron ores and are grouped into classes based on their phosphorus content. The manganese content is not as high as in other manganiferous ores of the district. The total shipments exceed 2,000,000 tons. Because of the rather fine structure and high moisture content, much of the crude ore requires sintering. The sintering plant is the largest of its kind in the United States for treating limonitic ores (50). Many innovations have been introduced here in the sintering of such ores. A washing plant is now being built to treat cherty ores. Its success is at least partly certain, judged by small-scale experiments, and with that adjunct the remaining reserves may

become many million tons. The iron-ore sinter contains 45 per cent of iron and 5 per cent of manganese (natural).

(7) *Croft mine* (red low-phosphorus ores).—This is the deepest of the underground mines. The shaft is now being sunk to the 630-foot (192-meter) level. The ore deposit is an unusually narrow lens, a mile (1.6 kilometers) long and 40 to 60 feet (12 to 18 meters) wide, on a southward-dipping monocline. The deposit is unique in that great depth is achieved, even though the width is small, and in that the entire output of ore is very low in phosphorus. It is the only mine that ships Bessemer ore. The iron content is also very high, being 59.80 per cent dry (53.67 per cent natural). The ore is purplish red and of rather fine structure. It is not treated. The total production is over 1,500,000 tons; the annual output about 175,000 tons.

(8) *Maroco mine* (washing and jigging; reddish-brown iron ore).—In the pit of the Maroco mine may be seen the narrow north limb of the major syncline, and owing to drag folding on the dip and a strong southwest pitch several local troughs were formed which became the sites of the best concentration. Concentration in other parts of this formation developed sandy ores, which had to be washed in log washers, and cherty ores which had to be jigged. The physical structure of the concentrates was almost ideal. The introduction of jigging apparatus, an innovation in the treatment of iron ores, bids fair to be applied extensively. More than 1,500,000 tons has been shipped, and the deposit is now about exhausted.

(9) *Merritt mine* (tabling and flotation; black manganiferous ores).—This mine is on the lower of the two bands of the North Range (39). The deposit is situated in a local syncline, pitching sharply to the northeast and opening widely in a distance of 1,000 feet (305 meters). The ores in this area are preponderantly the black or low-phosphorus high-silica manganiferous ores. An experimental plant is operated, using tables and oil-flotation cells. Silica of 14 per cent content in the crude ore is reduced to about 10 per cent, and manganese is increased from 14 to 18 or 20 per cent. The operators expect to improve on this and make an ore suitable for conversion into spiegeleisen. The ore is ground between rolls and classified for use on tables, and the fines and table tailings are run through the flotation unit. Production has not yet become continuous.

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THE MESABI RANGE

By John W. Gruner

The Mesabi range is a belt of low ridges that forms the watershed between the waters of Lake Superior and those of Hudson Bay. On the south slope of the range and parallel to it the Biwabik iron formation and its accompanying formations are found. Though the magnetites east of Mesaba station had attracted attention as early as 1866, the productive part of the range, because of the scarcity of outcrops, was not discovered until 1891.

GENERAL GEOLOGY

In general the rocks lie in belts of a northeastward trend. The geologic sequence is given in the table below:[6a]

Quaternary system:
- Pleistocene series—Glacial drift.

Unconformity.

Cretaceous system: Conglomerates and shales.

Unconformity.

Algonkian system:
- Keweenawan series—Duluth gabbro and associated diabase sills and dikes.
- Unconformity.
- Huronian series—
  - Upper Huronian (Animikie group)—
    - Virginia slate.
    - Biwabik formation (iron-bearing).
    - Pokegama quartzite.
  - Unconformity.
  - Lower-middle Huronian—
    - Giants Range granite.
    - Slate-graywacke, conglomerate formation (Knife Lake series).

Unconformity.

Archean system: Greenstones and schists.

ARCHEAN SYSTEM

Most of the greenstones are green to gray schists and represent much altered basic igneous rocks and, to a minor extent, sediments. Where foliation of the rocks is pronounced the name schist is preferable to greenstone.

[6a] This classification is that published in U. S. Geol. Survey Monograph 52. A revised classification is given on pp. 8–9.

ALGONKIAN SYSTEM

LOWER-MIDDLE HURONIAN GROUP

Graywackes and slates.—The graywackes and slates look somewhat like the Archean greenstones and schists, but their sedimentary character is shown by bedding planes in many places. The graywackes and slates are found in the area north of the Pokegama quartzite between Biwabik and Virginia.

Giants Range granite.—Granite intrudes the greenstone, the graywacke, and the slate and forms most of the hills which make up the Giants Range.

UPPER HURONIAN (ANIMIKIE) GROUP

Pokegama quartzite.—The upper Huronian sediments lie on the truncated edges of the lower-middle Huronian graywackes and slates. The Pokegama quartzite consists of a conglomerate at the base and a micaceous gray, green, or pink quartzite above the conglomerate. The total thickness of the quartzite ranges from a few feet to 200 feet (61 meters).

Biwabik iron-bearing formation.—Overlying the quartzite practically conformably is the Biwabik iron-bearing formation, about 400 to 750 feet (122 to 229 meters) thick. A detailed description is presented on pages 90–91.

Virginia slate.—The Virginia slate overlies the Biwabik formation conformably on the south side of the range. The two formations are separated by a persistent layer of impure crystalline limestone with an average thickness of about 10 feet (3 meters). The slate is usually gray and varies in hardness. Much of the rock easily splits along the bedding planes, but some breaks with difficulty and shows conchoidal fracture. The total thickness of the slate is probably several thousand feet.

KEWEENAWAN SERIES

Duluth gabbro encroaches on the iron formation in the eastern part of the range. Basic and dioritic offshoots from the gabbro are injected in the iron formation even as far west as the Belgrade mine. Other intrusives in the iron formation have been reported from the Eveleth and Keewatin areas.

CRETACEOUS SYSTEM

Conglomerates and shales overlie a number of ore bodies west of Eveleth. Cretaceous fossils have been found in the shales west of Hibbing.

QUATERNARY SYSTEM

PLEISTOCENE SERIES

On the Mesabi range from Mesaba westward probably not more than half a dozen exposures of the Biwabik formation can be found. In all other places a mantle of glacial drift, from 100 to 300 feet (30 to 91 meters) thick, or more, conceals the formation. The drift is thickest at the west end and thinnest at Mesaba, east of which outcrops of the fresh iron-bearing formation are very numerous.

BIWABIK IRON FORMATION

To the rocks of the iron formation the term taconite is applied. Taconite is a banded ferruginous chert containing some slaty layers and some carbonates. Much of it has a peculiar granular texture. The granules may consist of chert, iron oxides, or greenalite, or a mixture of these. Greenalite is a more or less well-defined ferrous silicate of grayish-green color. Its granules are similar to oolites in shape and texture but lack the internal concentric shell structure of oolites. Most of this greenalite is really very fine-grained iron amphibole, and the chert is very fine-grained quartz.

The chemical composition of the average taconite, as given by Van Hise and Leith (51, p. 181),[7] is as follows:

Fe	25.71
SiO_2	58.70
P	.021
Al_2O_3	.54
Loss on ignition	1.96

Many of the layers of taconite, however, are higher in iron. In these the iron is mostly in the form of magnetite and can be extracted almost completely after fine grinding of the taconite. The magnetite occurs either as bands or as granules of the shape of greenalite grains.

On the easternmost 14 miles (22.5 kilometers) of the Mesabi range the minerals of the iron formation are coarser in grain, and more iron amphibole is developed. This metamorphism is attributed to the action of the gabbro, which probably overlay the Biwabik formation as a very thick sill. Magnetite in rich layers of considerable thickness is so extensive and easily accessible from the surface that much energy and money have been expended in experiments on its mining and concentration (42). In the productive portion of the range there are areas that contain enormous tonnages of taconite in which the iron content in the form of magnetite averages 25 per cent.

[7] Numbers in parentheses refer to bibliography, p. 97.

The Biwabik formation in general dips gently to the south—on an average at an angle slightly smaller than 10°. There are no close folds and only two relatively large faults and one sharp monocline in the whole formation. In the vicinity of Virginia and Eveleth the formation makes a peculiar Z-shaped bend, which is usually called the "Virginia Horn." (See pl. 8.) The iron formation undoubtedly covered the older formations within the "Horn" at one time.

The iron formation has been divided into four units on lithologic differences. It contains two great horizon markers—a most persistent black slate layer and an organic chert layer with fossil algae. A section of the recognized divisions follows:

Divisions of the Biwabik formation

	Feet	Meters
UPPER SLATY DIVISION		
Limy carbonate, with greenalite, greenalite slate, and slaty taconite	0–25	0–7.6
Slaty and cherty taconite, greenalite, and slate	0–145	0–44
UPPER CHERTY DIVISION		
Cherty, banded, slaty, and greenalite taconite with layers of conglomerate. Algal structures. Some beds rich in magnetite	95–250	29–76
LOWER SLATY DIVISION		
Slaty taconite, greenalite, greenalite slate, banded and cherty taconite, carbonates, and scattered conglomerates. Some rich magnetite beds	0–250	0–76
"Intermediate slate." Black slate, greenalite slate, and paint rock	½–40	0.15–12
LOWER CHERTY DIVISION		
Lean member. White cherty and greenalite taconite, greenalite, and greenalite slate	12–52	3.7–16
Member rich in magnetite. Irregularly banded, mottled, and greenalite taconite	90–250	27–76
Member with iron in ferric state:		
Cherty and banded taconite with slate and slaty taconite on top	8–70	2.4–21
Red basal taconite	0–40	0–12
Basal conglomerate and algal structures	0–12	0–3.7
	400–755	122–230

HEMATITE AND LIMONITE ORES

According to Wolff (54, p.245) there are three kinds of ore—(1) a high-grade blue or brown ore, averaging, dry, 59 per cent of iron; (2) a medium-grade brown or yellow ore, averaging,

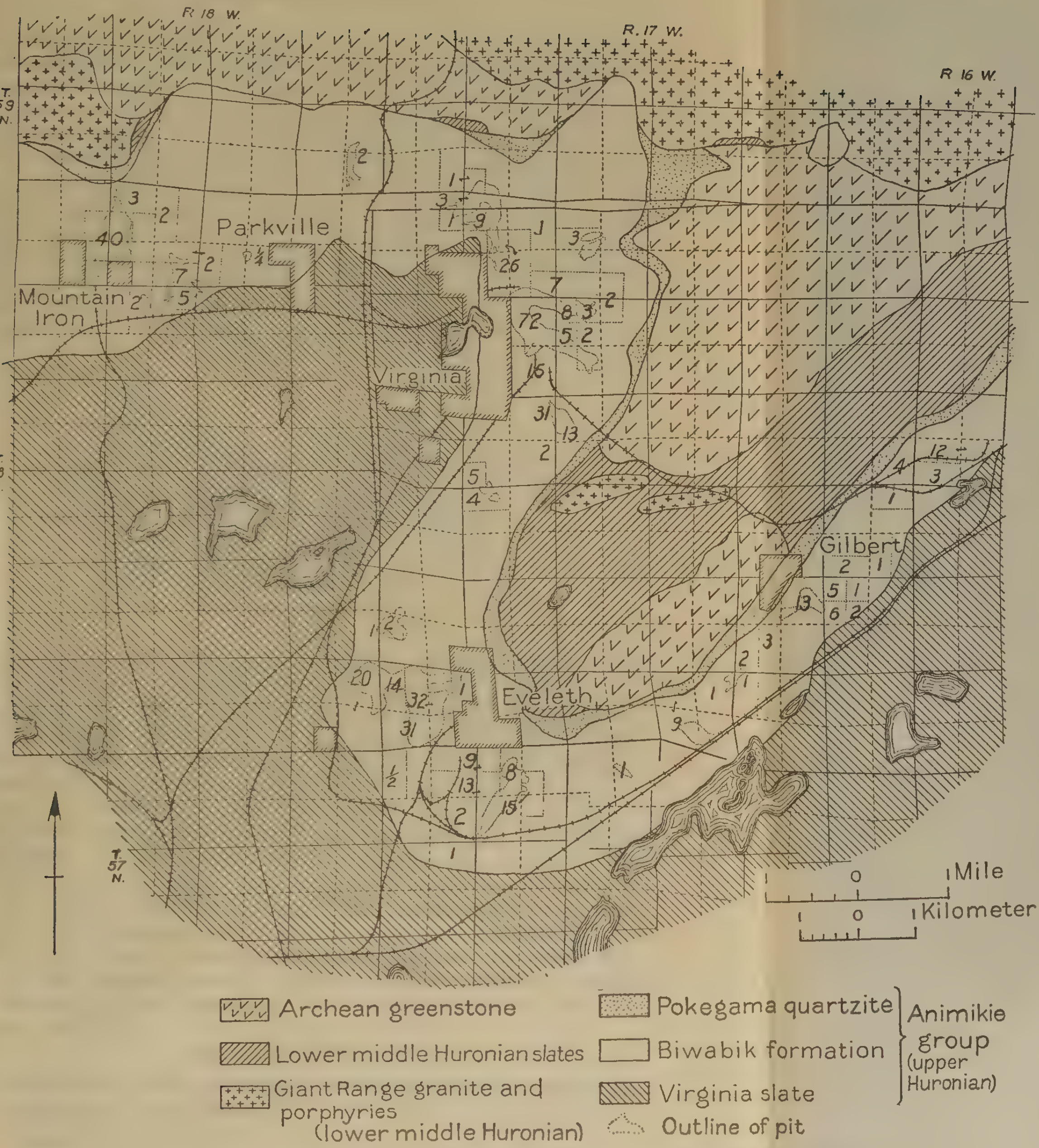
dry, 55 to 56 per cent of iron; and (3) a low-grade yellow or brown ore, averaging, dry, about 50 per cent of iron.

The blue ore is a Bessemer ore found in the lower and upper cherty divisions and in parts of the lower slaty division. The brown ore occurs in all except possibly the lower cherty division. The yellow ore occurs in the lower cherty division, at the top and, in a few parts of the range, at the bottom. The ore at the top is easily recognized where it is in contact with the red intermediate paint rock. The yellow ore may occur also anywhere above the paint rock, where the original rock consisted mainly of greenalite.

It is possible to correlate the different ores with the unaltered members of the formation from which they were derived. Examination of thousands of drill cores and much microscopic study have shown that certain minerals on decomposition change to definite alteration products. For example, much magnetite in a drill core means blue martite ore at the corresponding horizon in the ore body. If a larger amount of slate is interlayered with the magnetite the ore becomes brown. Predominating greenalite in the rock, on the other hand, usually produces yellow ore. Much slate with the greenalite may make the yellow ore derived from them nonmerchantable. Lean greenalitic taconite, as it occurs in most parts of the upper slaty division, very rarely yields a commercial lean ore. Black slate alters to ore only under conditions of replacement by hematite and limonite. Usually it forms the paint rock, which is high in alumina. On the western part of the range (west of Keewatin) certain layers of ore are too high in silica to be shipped directly. The silica, being in the form of a friable "sandy" material, can be removed by washing, however. Such ores are called wash ores. Before removal of the quartz grains (not of clastic origin, but due to recrystallization) the wash ores are lighter in color than the regular ores. After washing these ores may be assigned to the same classification as the standard types.

SHAPE AND STRUCTURE OF ORE BODIES

The ore bodies were classified by Wolff (54, p. 236) into trough-shaped ore bodies, fissure ore bodies, and flat-lying ore bodies. The most important type economically comprises the trough-shaped bodies. In size they range from large fissures to some that have a length of nearly 1 mile (1.6 kilometers), a width of 1,000 feet (305 meters), and a depth of 200 to 500 feet (61 to 153 meters). At some places two or more troughs run parallel for a distance, then converge, and ultimately unite into one body. Some of the troughs intersect. These troughs are formed by the leaching of the silica out of the taconite, with



GEOLOGIC MAP OF THE "VIRGINIA HORN" OF THE MESABI RANGE

Figures indicate ore, in millions of tons, on the several properties as recorded by the Minnesota Tax Commission.

the creation of much pore space. As the porous residual masses of iron oxides are unable to support the overlying burden of ore and rock they slump, with the consequent elimination of a large part of the pore space. As the original bedding planes are preserved to a considerable extent in spite of the movement of the ore downward, the result is an easily recognizable synclinal structure of the ore between the rock walls, which remain in their original position. (See fig. 22.) The slump in the ore bodies is very considerable. In a vertical column of solid taconite, originally 100 feet (31 meters) high, the shrinkage may amount to 40 feet (12 meters), if all the taconite is converted to ore. The direction of the troughs is practically always parallel to one of the major sets of jointing of the taconite.

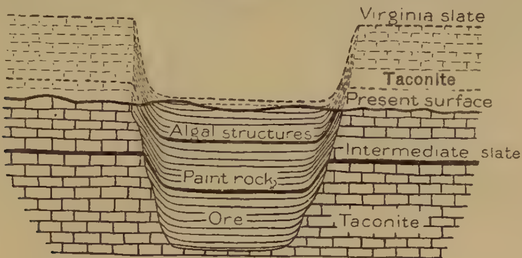


FIGURE 22.—Ideal cross section through a trough ore body

The fissure ore bodies are very similar to the trough-shaped bodies in every respect except size. The width may be only 2 or 3 feet (0.6 to 0.9 meter), or even less, and the depth 50 feet (15 meters) or more. The length may exceed 200 feet (61 meters). Naturally the fissure bodies are commonly arranged in parallel lines following the joints that determined their positions. As there are several intersecting joint sets, the fissure ore bodies also commonly intersect one another at corresponding angles. These fissure ore bodies and also parts of the trough-shaped bodies do not necessarily come to the surface. Some of them reach the bottom of the intermediate paint rock but do not penetrate upward into it as far as is known.

The flat-lying ore bodies have been described by Wolff (54, p. 236) as troughs cut off. These bodies are shallow, chiefly on account of the thinness of the iron formation in the particular localities.

ORIGIN OF THE ORES

Some facts of importance for an understanding of the origin of the ores are stated below:

1. The ore was formed by the leaching of vast amounts of silica from the iron formation. Most of the silica was in the form of very fine-grained quartz.

2. Practically all ferrous iron in the areas of the ore bodies was oxidized to ferric oxides and hydroxides before and during the removal of the silica, as shown especially well in drill cores.

3. At the time of the formation of the ore all the iron formation was practically in the same mineralogic and textural condition in which it is to-day, as shown by gradational phases.

4. The concentration of the ore was practically completed at the beginning of Upper Cambrian time. This is inferred from the conditions existing on the ranges in Michigan.

5. Large ore bodies extend to a depth of 900 feet (274 meters), a condition which means that exceptionally as much as 150 feet (46 meters) of Virginia slate may overlie the deep portions of ore bodies.

6. Practically all magnetite of the original taconite is oxidized to martite in the ores, regardless of depth.

7. The ore bodies are concentrated to a considerable degree in certain areas. Their longer axes are more nearly parallel to the strike than to the dip of the formation west of Mountain Iron. East of this town their axes are more irregular on account of the bend of the Virginia Horn.

8. It has been impossible so far to correlate the positions of the ore bodies with any structural basins. On the contrary, the ore bodies in the Eveleth area (pl. 8) occur on the nose of a pitching anticline.

9. Fairly well defined steep and high walls of little-altered taconite are found in the deposits, especially east of Mountain Iron.

10. Very many ore bodies terminate rather abruptly up the dip of the formation. They are, therefore, separated from the north edge of the Biwabik formation by a "wall" of unleached taconite.

11. The ore bodies seem to have no impervious floors or foot-walls. Larger bodies may send ore "shoots" and fissures into the walls, commonly under the intermediate layer of paint rock.

12. Most deposits are somewhat wider near the surface than below.

13. The deposits are apparently related to the preglacial erosion surface, though there is proof (fig. 22) that in many, if not most, places at least 125 feet (38 meters) of iron formation have been removed since the ore was concentrated. Figure 22 shows that taconite layers corresponding stratigraphically to the upper portions of the ore bodies have been eroded.

14. No leached ore occurs east of Mesaba (except in the small Spring mine), where the Duluth gabbro intruded along the top of the iron formation has recrystallized it.

PRODUCTION AND RESERVES

Some figures on production, quality, mining costs, and ore reserves of the Mesabi range are given below.[8]

Production and average analyses of ores mined on the Mesabi range

Year	Ore mined (tons)	Fe	P	SiO_2	Total moisture
Bessemer ores					
1919	11,104,863	53.74	0.044	7.45	10.68
1925	10,443,065	54.87	.039	8.12	9.03
1930	8,747,345	54.11	.039	8.83	9.23
Non-Bessemer ores					
1919	19,092,807	50.35	0.078	7.87	12.77
1925	24,924,821	50.91	.071	7.87	12.03
1930	22,105,843	50.07	.075	8.19	12.76
Total					
1919	31,136,408	51.50	0.066	7.75	12.03
1925	35,530,956	52.05	.061	7.99	11.14
1930	30,955,501	51.20	.065	8.40	11.74

[8] Data from Craig, J. J., Mining directory of Minnesota: Minnesota Mines Exper. Sta. Bull. 31, 1931.

Value per gross ton of iron ores from the Mesabi range and transportation costs, 1929–1931

Class	Value at mines	Rail freight to upper Lake ports	Dumping charge
Bessemer	$2.86	$0.81	$0.10
Non-Bessemer	2.71	.81	.10

Class	Lake freight to lower Lake ports	Unloading charge	Interest and insurance	Price at Lake Erie ports
Bessemer	$0.70	$0.13	$0.05	$4.65
Non-Bessemer	.70	.13	.05	4.50

Mining costs on the Mesabi range, 1929

	Total ore mined (gross tons)	Total cost of development and mining	Average development cost per ton
Open-pit operations	37,862,622	$40,081,675	$0.260
Underground operations	9,060,289	17,772,779	0.55

	Average mining cost per ton				Average royalty paid per ton [b]	Average total cost [c]
	Labor	Supplies	Other items [a]	Total		
Open-pit operations	$0.112	$0.124	$0.113	$0.349	$0.449	$1.058
Underground operations	.862	.416	.189	1.467	.447	1.969

[a] Includes administrative and overhead expenses, depreciation, and other miscellaneous costs attributable to the mining of ore. Depletion, interest on capital and the like, where known, are not included.

[b] Based on total tonnage mined, exclusive of fee ore.

[c] Includes total development, mining, and royalty costs. Does not include beneficiation costs, taxes, marketing costs, depletion, interest on capital, and certain other overhead expenses.

Beneficiated iron ore from the Mesabi range in 1930, in gross tons

Washing	4,877,518
Jigging	895,359
Sintering	45,673
Crushing and screening	7,172,774
	12,991,324
Per cent of total ore shipments	41.8

The iron ore reserves of the Mesabi range on May 1, 1930, according to the Minnesota Tax Commission, amounted to 1,154,434,031 tons. This figure does not include low-grade ore, which is estimated by the commission as 200,000,000 tons—probably a very low estimate.

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ITINERARY

Duluth is situated at the west end of Lake Superior, where the St. Louis River discharges its waters into the lake. A curving sandbar 7 miles (11 kilometers) long separates the mouth of the river from Lake Superior proper. A good harbor has been constructed behind this bar by cutting a channel through it on the north end. Duluth, with a population of 101,463 (1930), is said to have a larger tonnage cleared each year than any other inland harbor in the world. At Thirty-third Avenue west are the great docks from which much of the Mesabi ore is shipped.

The conspicuous feature of Duluth is an escarpment rising close to the shore of Lake Superior, so straight in a large way as to suggest a fault. Most of the rocks east of the centre of the city are surface volcanic rocks of the Keweenawan series. From

the center west the bluff consists of the great intrusive Duluth gabbro in enormous exposures and with several petrographic phases. (See p. 70.) There is a terrace near the top of the bluff, about 500 feet (152 meters) above Lake Superior, on which beach gravel shows the altitude of a glacial lake. It was early found that with little grading this terrace made an excellent natural road, and it is now used for a scenic drive. The view from the terrace or from the top of the inclined railway is especially fine on a clear day or when Superior and Duluth are lighted up in the evening.

As the roads and railroads to the west climb the bluff they give a view of the steel plant and cement mill in the western part of the city, along the St. Louis River.

Duluth to Eveleth (58 miles, or 93 kilometers).—After leaving the great escarpment of the Duluth gabbro north of Duluth, the trip on the Miller trunk highway to Eveleth is very monotonous. There are no outcrops of the bedrock known along this route, as glacial drift covers this part of the great peneplain. From a point 10 miles (16 kilometers) south of Eveleth can be seen the chain of ridges called the Mesabi or Giants Range. Notwithstanding its altitude of not more than 300 feet (91 meters) above the peneplain, it is a conspicuous landmark. The large buildings on the southernmost hill are the Eveleth high school and junior college.

Eveleth, with a population of 7,484, is supported almost entirely by the mining industries. On the highway to Virginia, but still in the city of Eveleth, is a small cut through magnetic taconite. The micaceous phase of the Pokegama quartzite is exposed in a small quarry at the north end of Eveleth, along the grade of the old electric traction line.

A good view of the Adams, Spruce, and Leonidas open pits may be had from a point west of the northwest corner of Eveleth. These three pits work three major ore troughs, which extend through all four divisions of the iron formation. The major troughs have an east-west trend and are more or less parallel. Minor troughs connect the large ones, giving rise to one enormous ore body of more than 110,000,000 tons of merchantable ore.

The Adams pit is about 200 feet (61 meters) deep, but ore is known to extend to much greater depth. The so-called paint-rock layer, which was originally a black slate (intermediate slate) but now is ore in part, may be traced completely around the pit. Its red color is an infallible horizon marker for the mining engineer in distinguishing the lower cherty division below it from the lower slaty division above it. The ore below the paint rock is of high-grade Bessemer quality; the ore immedi-

ately above it is a non-Bessemer ore, easily recognized by its yellow color. Above this yellow ore the grades of ore vary.

About 200 feet (61 meters) above the paint-rock layer is the layer showing algal structure in the ore of the upper cherty division. These structures, which are silicified remains of the algae, can be recognized readily by their contorted and gnarled banding (45, p. 16). The algal layer may be traced from the west side of the Adams pit into the Leonidas pit, where it formed the bottom of the so-called "upper ore body," now mined out. This ore body extended upward to the Virginia slate. The "upper ore body" is separated from the "lower ore body" by about 100 feet (30 meters) of oxidized but unleached taconite. Some fissure ore bodies, however, connect the two. The lower ore body, which is mined by underground methods, extends downward practically to the Pokegama quartzite as far as is known. It contains over 12,000,000 tons of ore. A conglomerate made up largely of pebbles of ore and iron formation overlies portions of the Leonidas ore body unconformably. It grades upward into a shaly sediment. As no fossils have been found in these sediments their age is unknown. They closely resemble the Cretaceous conglomerates and shale west of Hibbing.

Eveleth to Virginia (4 miles, or 6.4 kilometers).—On the west side of the road beyond Eveleth is a high cliff that represents the lower third of the lower cherty division of the Biwabik formation. The top of the outcrop consists of strongly magnetic taconite. Just opposite the cliff, but east of the highway along the old railroad grade, the lower-middle Huronian slates and graywackes are exposed. Patches of the basal conglomerate of the Pokegama quartzite form a very thin veneer on portions of the slates and graywackes and display what is probably the greatest unconformity of the region.

The city of Virginia (population 11,963) is built on Virginia slate, but this formation does not crop out near the city. From the east end of Chestnut Street it is possible to get a glimpse of the Missabe Mountain pit, which is in one of the biggest and richest ore bodies of the range. The ore in the deepest part is over 450 feet (137 meters) in vertical extent and extends from the now removed highly altered Virginia slate to the bottom of the iron formation. The steep walls of the ore "troughs" are especially well exposed in the Norman and Commodore extensions, in which the intermediate paint rock is also visible. (For tonnage of ore see pl. 8.)

Virginia to the Giants Range.—The road from Virginia to Tower crosses the Giants Range 3 miles (4.8 kilometers) northeast of Virginia. On the south slope of the ridges the contact between the older greenstones and the granite is exposed in

places. Inclusions are very numerous in the granite, but their number diminishes on the ridges toward the north, and on the north slope few if any inclusions of the intruded rock are visible. The granite is medium grained. The dark constituents are chiefly biotite.

A fine exposure of ellipsoidal greenstone is found just north of the high school at Gilbert, within 200 feet (61 meters) of the water tower. This place can be reached best from Virginia by the direct route through the "Virginia Horn," a distance of 4 miles (6.4 kilometers). Good exposures of the lower-middle Huronian slates and graywackes are also found along the road. The return trip to Virginia may be made by the Malta pit at Sparta, where a cut has been made in greenalite taconite in the "approach" to the pit. The Malta pit also furnishes an excellent example of fissure ore bodies, which, however, may not be visible if the pit is full of water.

Virginia to Hibbing (20 miles, or 32 kilometers).—The highway from Virginia to Hibbing passes through several villages, all of which boast of magnificent school buildings. A mile (1.6 kilometers) east of Chisholm, north of the paved main highway, is the Shenango pit, the deepest on the range, 350 to 375 feet (106 to 114 meters) deep. It illustrates the intersection of two deep trough ore bodies, one of them striking east, the other N. 50° W. The north wall of the pit is in solid taconite. Of the original 16,000,000 to 17,000,000 tons of ore 2,000,000 tons is still unmined. The ore reaches the Pokegama quartzite.

Hibbing is a city of 15,666 inhabitants. It boasts of the most expensive high school in the world. The present city is a product of the last 10 years, the old town having been abandoned in order to permit the mining of the ore underneath it. The ore bodies are intricately connected by trough and fissure bodies. Altogether they contained probably 500,000,000 tons of ore, the Hull-Rust-Mahoning properties alone being credited with over 260,000,000 tons. The trends of individual troughs are usually N. 50° W. The staggering of a number of them in an east-west direction produces the great ore bodies of east-west elongation. Especially interesting is the very deep pit (350+ feet, or 107+ meters) of the Susquehanna mine (26,000,000 tons of ore). The glacial drift here is about 140 feet (43 meters) thick. The bottom of the ore has not been mined in any of these large pits in the immediate vicinity of the city, except in the Kerr mine, located entirely in the lower cherty division.

The interesting features of these mines are their vast extent and interlocking by large fissure ore bodies. The latter feature, however, can be studied only in cross sections prepared by the

mining companies. Lack of time will not permit closer study of the deposits in the vicinity of Hibbing.

Hibbing to Nashwauk and Calumet (21 miles, or 34 kilometers). At Nashwauk a large part of the ore mined is wash ore. In these ores the decomposition of the taconite just under the paint rock has produced a white sandy conspicuous layer in which vugs lined with small goethite crystals are common. This feature can be seen in the Hawkins pit (17,000,000 tons of ore). There also seems to exist a relatively large monocline in the Biwabik formation, as indicated by the steep dip of the beds in the adjoining La Rue mine. Otherwise these pits offer no new geologic features.

The Cretaceous ore conglomerates, which are composed chiefly of pebbles of limonite and hematite, are found on several ore bodies from Eveleth westward. They can be studied well in the Hill Annex pit at Calumet, 6 miles (9.6 kilometers) west of Nashwauk. This is also the best locality in which to see fossils in the Cretaceous shales and conglomerates. Shark teeth and mollusks, especially *Ostrea*, are very abundant and place the conglomerate and shale in the upper part of the Cretaceous. The Hill Annex pit is now entirely electrified. Electric shovels had been used for several years in some of the pits, but in the Hill Annex the steam locomotives have also been replaced by the more powerful electric traction engines. The Hill Annex ore body is one of the largest of the flat-lying type. It contains about 40,000,000 tons of ore, a large portion of which is wash ore.